

# Towards laser plasma accelerators for future colliders (and light sources)

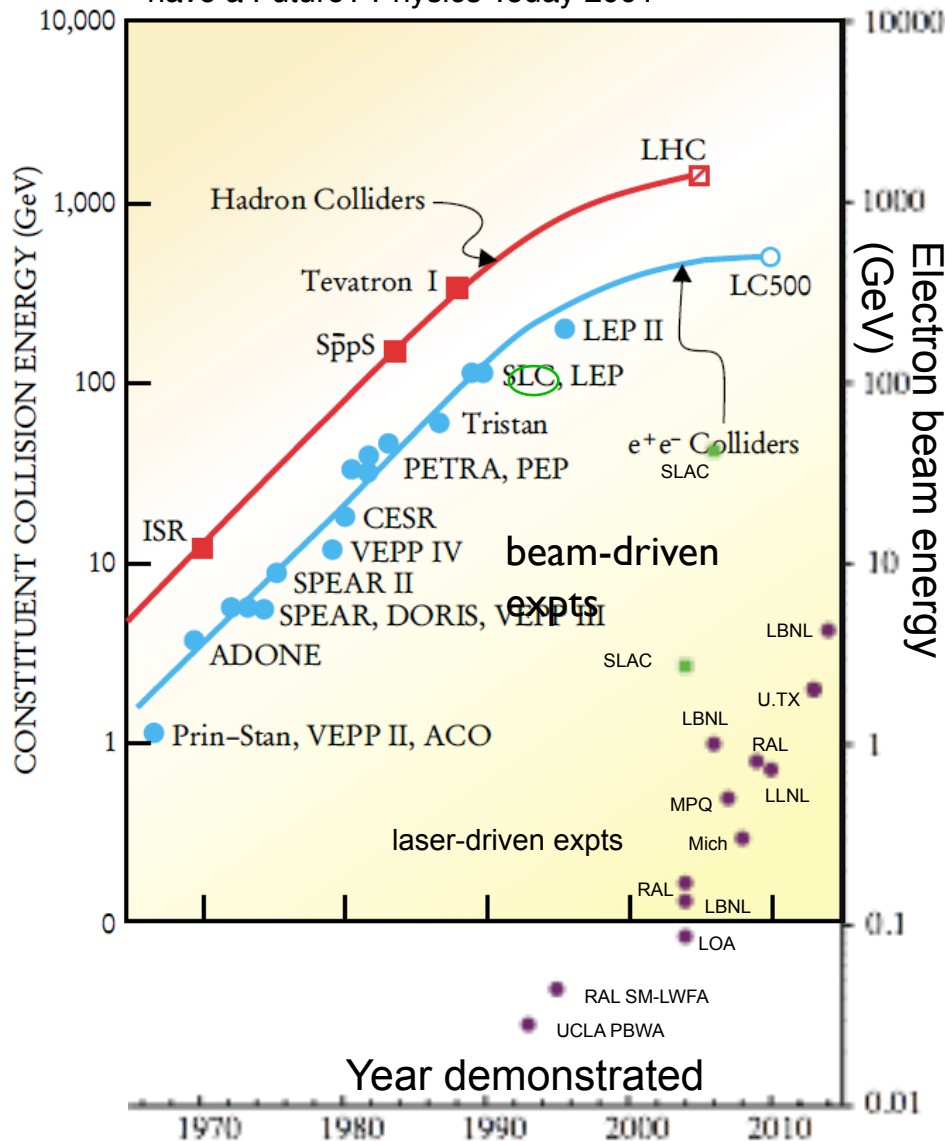


Wim Leemans  
*BELLA Center*  
*Lawrence Berkeley National Laboratory*

*Work supported by Office of Science, Office of HEP, US DOE  
Contract DE-AC02-05CH11231, the NSF and by NNSA DNN R&D, US DOE*

# High gradient (and hopefully lower cost) transformational accelerator technology is being developed

M. Tigner: Does Accelerator based Particle Physics have a Future? Physics Today 2001



## ■ From P5 report:

“The U.S. could move boldly toward development of transformational accelerator R&D.”...“For e<sup>+</sup>e<sup>-</sup> colliders, primary goals are improving the accelerating gradient and lowering the power consumption.”

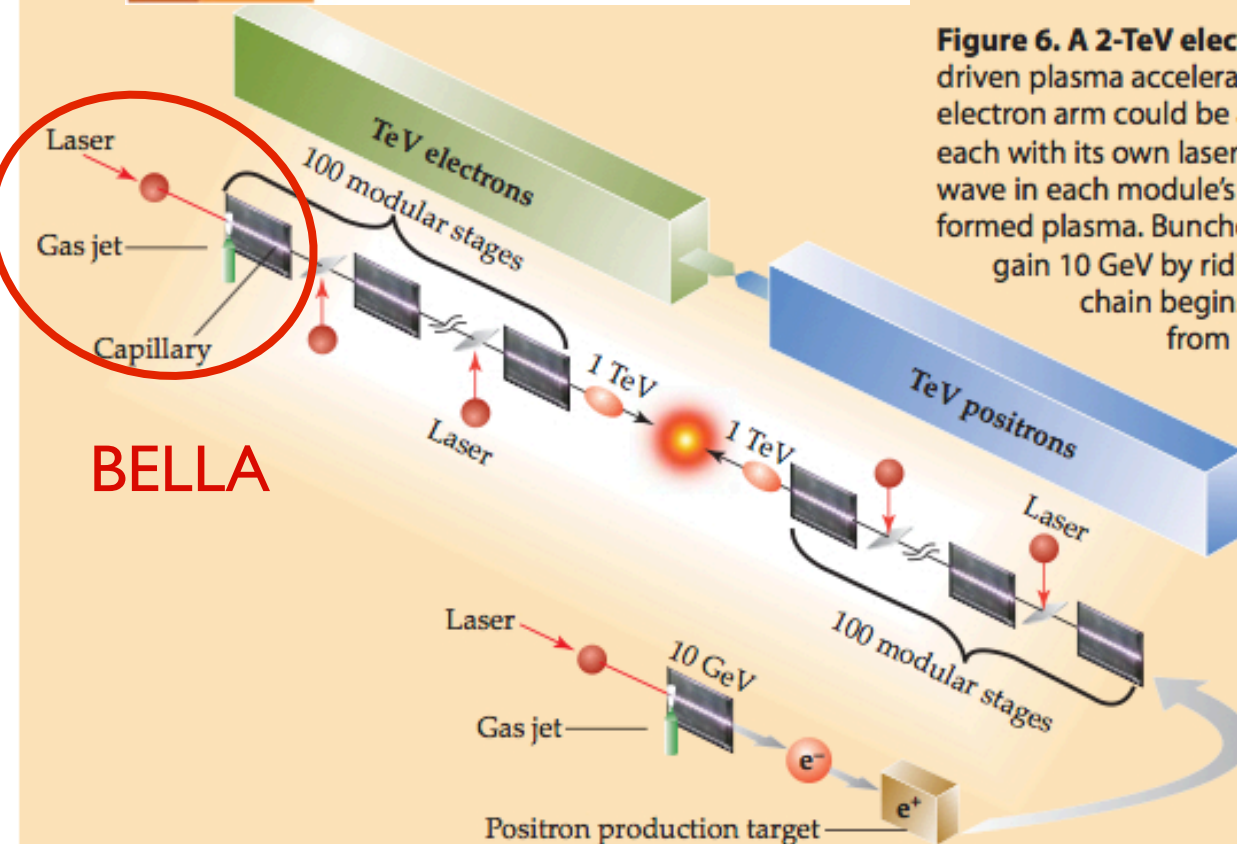
## ■ Significant progress worldwide in last 20+ years exploring these concepts

## ■ This talk presents a snapshot of where LBNL's progress is



# Laser-driven plasma-wave electron accelerators

Wim Leemans and Eric Esarey



BELLA

**Figure 6. A 2-TeV electron-positron collider** based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

March 2009 Physics Today

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 13, 101301 (2010)

## Physics considerations for laser-plasma linear colliders

C. B. Schroeder, E. Esarey, C. G. R. Geddes, C. Benedetti, and W. P. Leemans  
 Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA  
 (Received 11 June 2010; published 4 October 2010)

# Laser plasma acceleration (LPA) relies on laser excited fields in plasmas

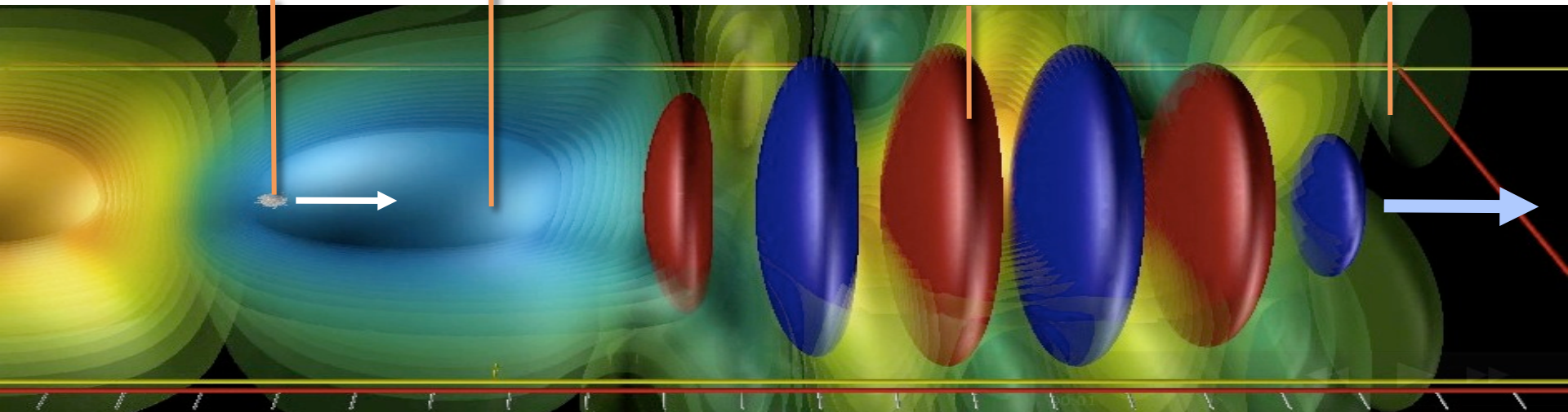


surfer  
e- beam

wake

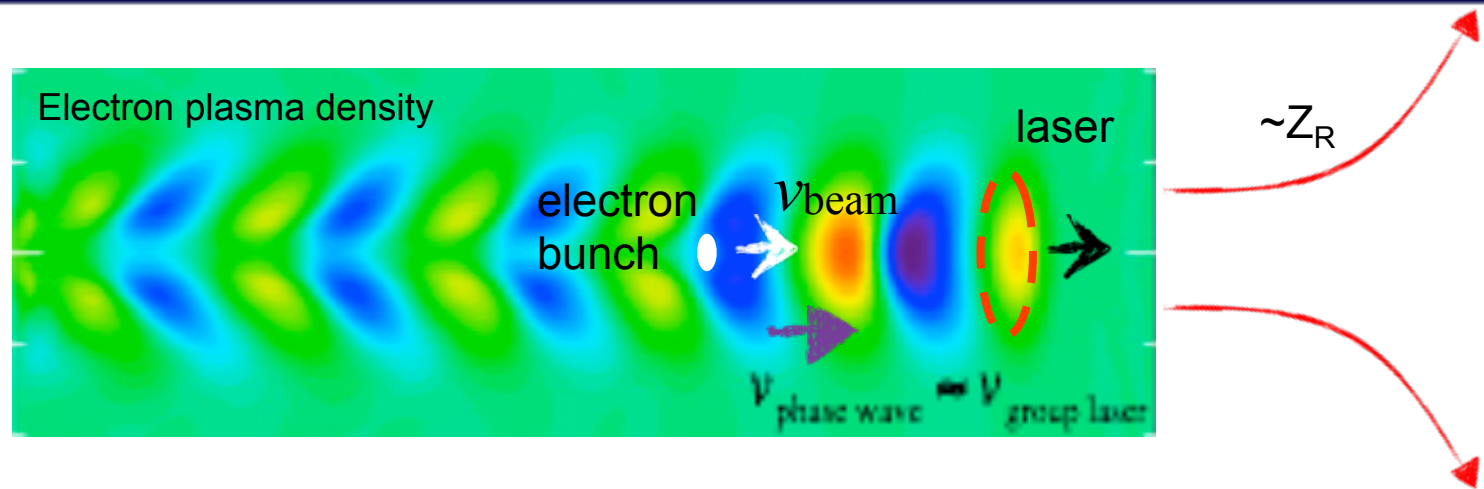
boat  
laser

water  
plasma





# Limits to energy gain in laser-plasma accelerator (LPA): diffraction, dephasing, depletion



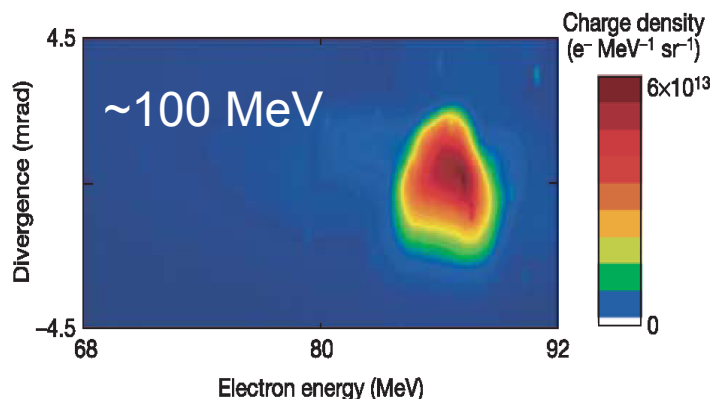
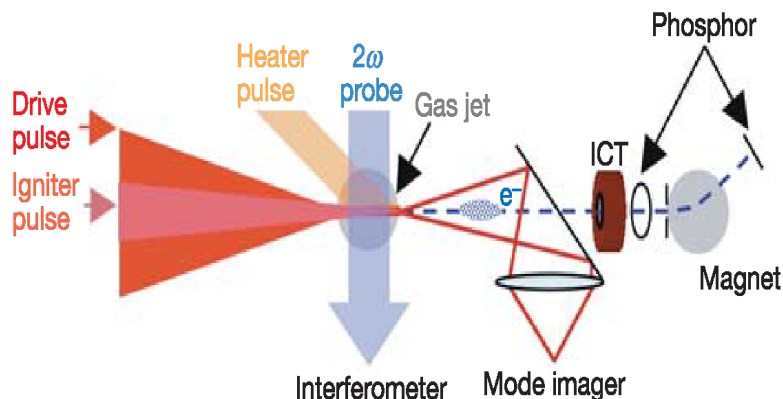
**Limits to single stage energy gain:**  $mc^2 \Delta\gamma \sim q(mc\omega_p/e)L_{\text{int}}$

- **Laser Diffraction:**  $\sim$  Rayleigh range (typically most severe)
  - Controlled by transverse plasma density tailoring (plasma channel) and/or relativistic self-guiding and ponderomotive self-channeling
- **Beam-Wave Dephasing:** Slippage between e-beam and plasma wave
  - Controlled by longitudinal plasma density tailoring (plasma tapering)
- **Laser Energy Depletion:** Rate of laser energy deposition of into plasma wave

$$L_{\text{deplete}} \propto n^{-3/2} \lambda^{-2}$$

# Channel guided laser plasma accelerators have produced up to GeV beams from cm-scale structures powered by up to 40 TW pulses

2004 result: 10 TW laser, mm-scale plasma

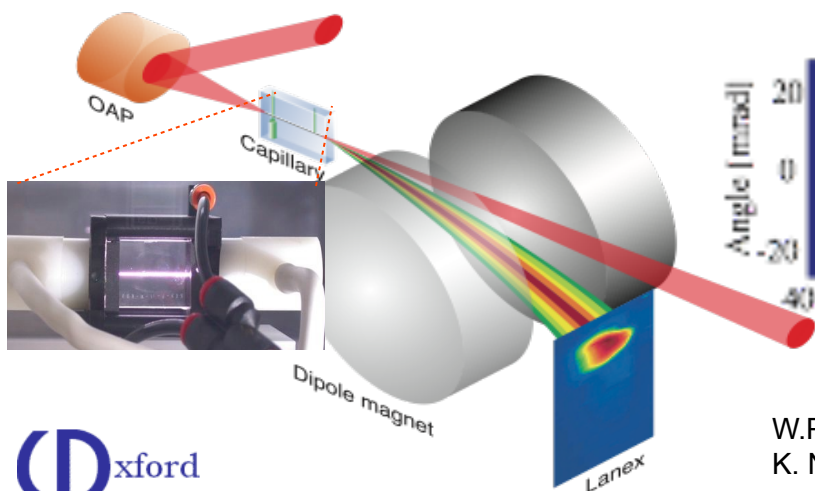


C. G. R. Geddes, et al, *Nature*, **431**, p538 (2004)

S. Mangles et al., *Nature* **431**, p535 (2004)

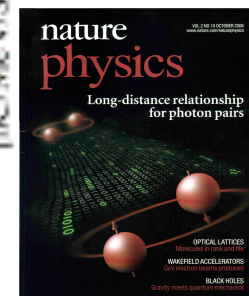
J. Faure et al., *Nature* **431**, p541 (2004)

2006 result: 40 TW laser, cm-scale plasma



W.P. Leemans et. al, *Nature Physics* **2**, p696 (2006)

K. Nakamura et al., *Phys. Plasmas* **14**, 056708 (2007)



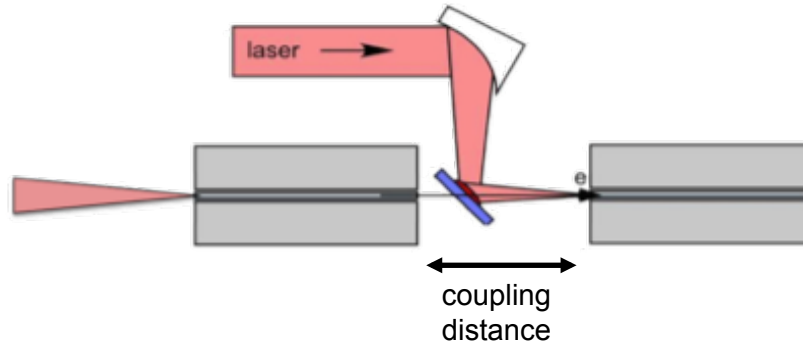


# Outline

- Staging of two independently powered LPAs
- Experiments with BELLA
- Towards high average power operations

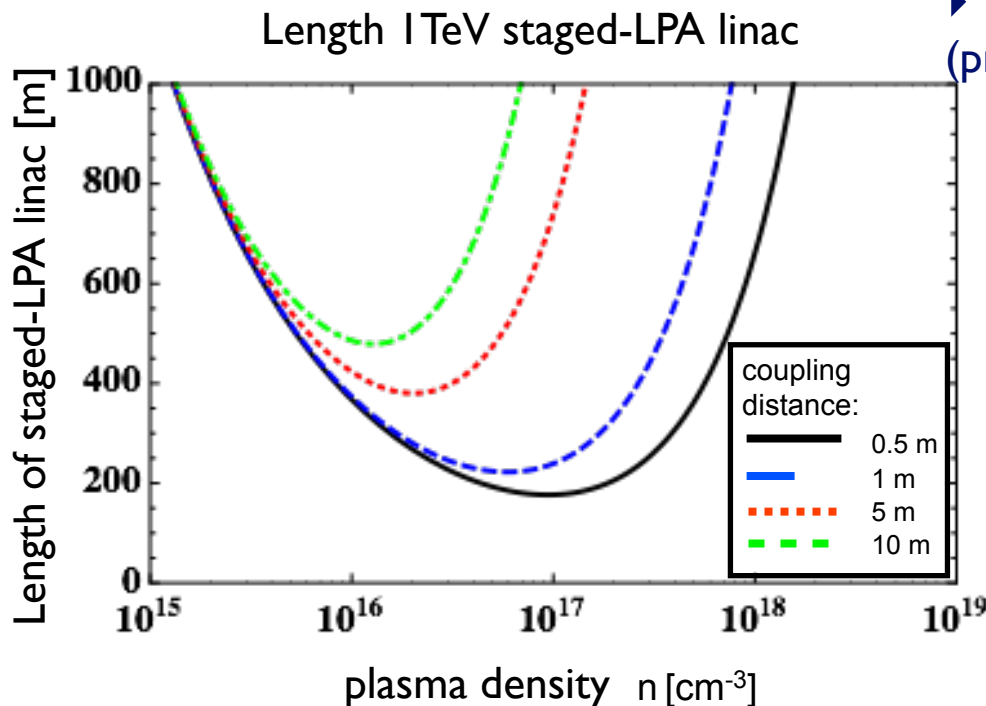
# Staged LPAs: average gradient determined by driver in-coupling distance

► LPA stage:



► Number of stages:

$$N_{\text{stage}} = U_{\text{beam}} / \Delta U_{\text{stage}} \propto n$$



► Laser in-coupling distance  
(provides for high-average gradient)

- **conventional optics:** requires many Rayleigh ranges reduce fluence on optic (avoid damage)

$$L_{\text{coupling}} \propto n^{-5/4} \lambda^{-1}$$

- **plasma mirror:** relies on critical density plasma production (high laser intensity): coupling  $< 1$  m



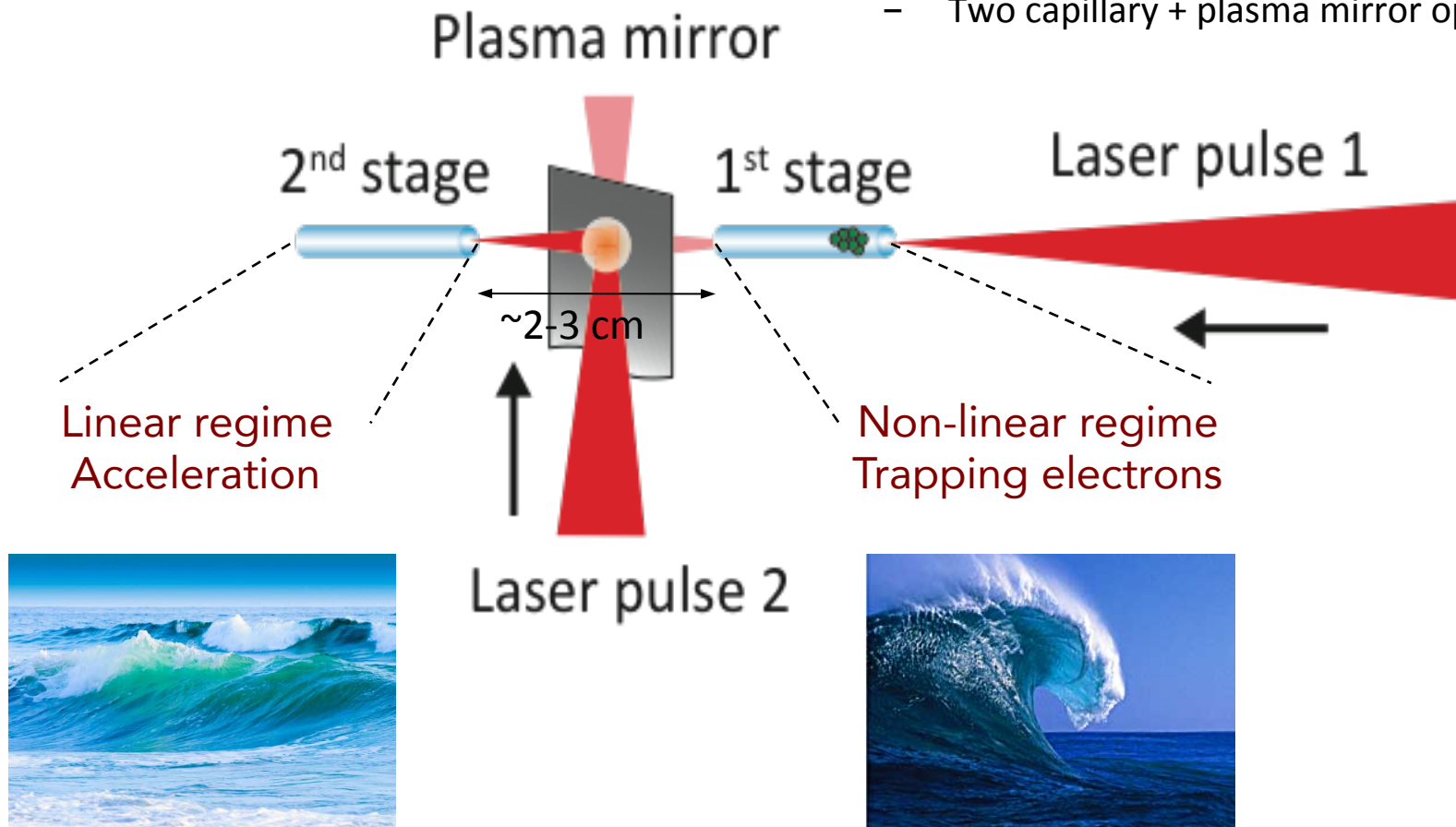
# Staging experiment aims at demonstrating key element of collider concept and requires precision

## Advantages:

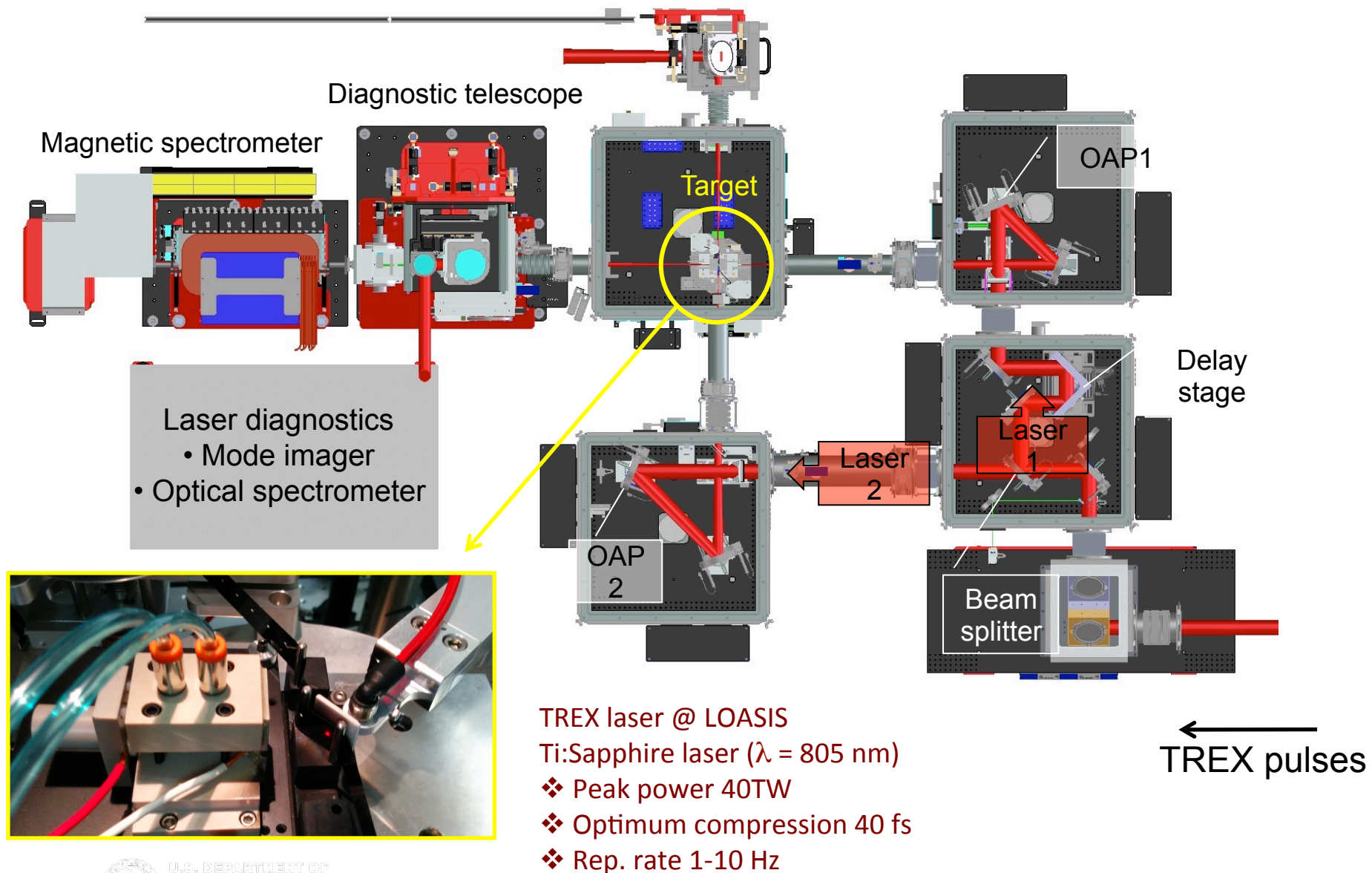
- Staged LPA can supply fresh laser pulses
- Separate injection and acceleration

## Challenges:

- Laser spatial overlap  $\sim \mu\text{m}$
- Temporal overlap  $\sim \text{fs}$
- Two capillary + plasma mirror operation



# The staging setup was initially designed in 2010-2011

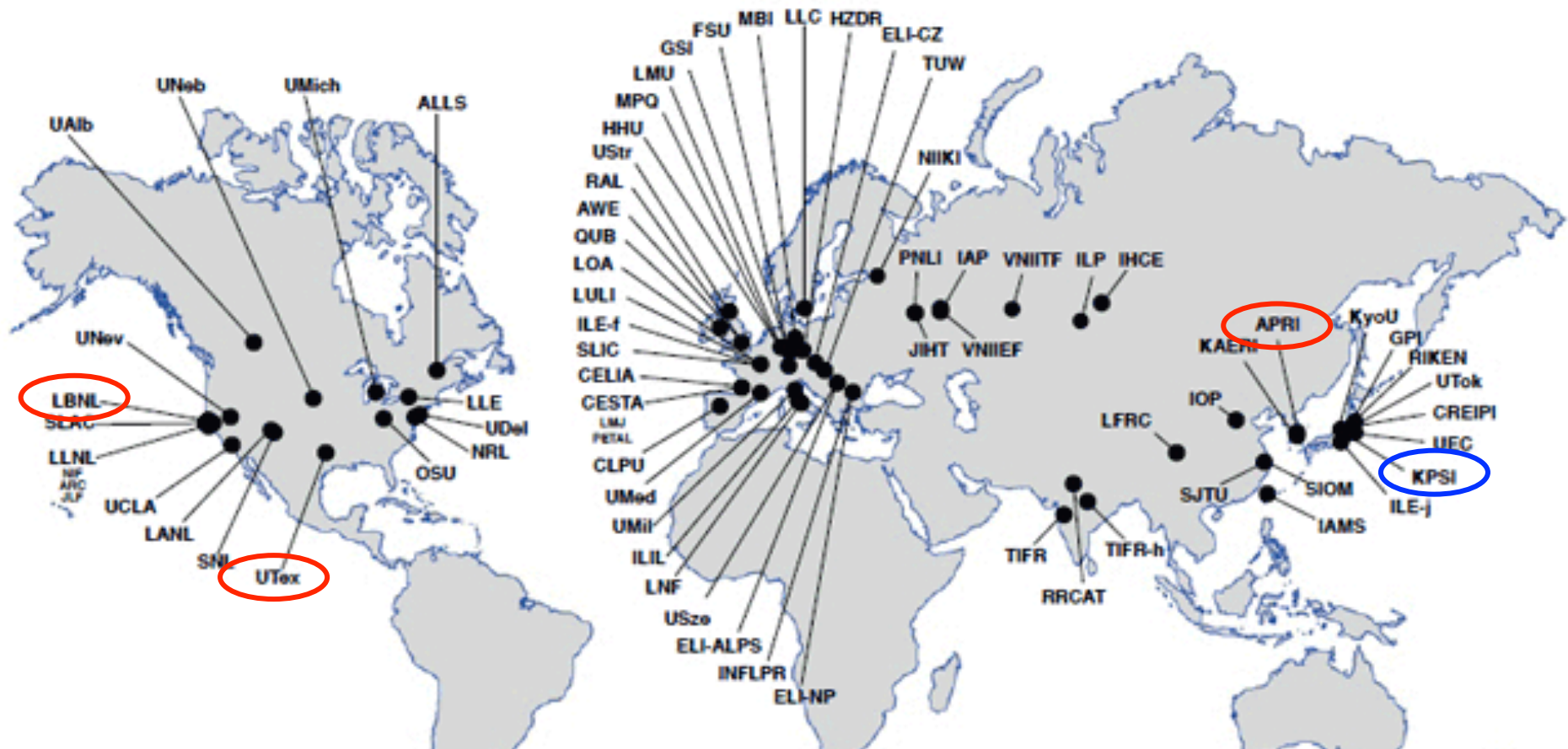




# Outline

- Staging of two independently powered LPAs
- **Experiments with BELLA**
- Towards high average power operations

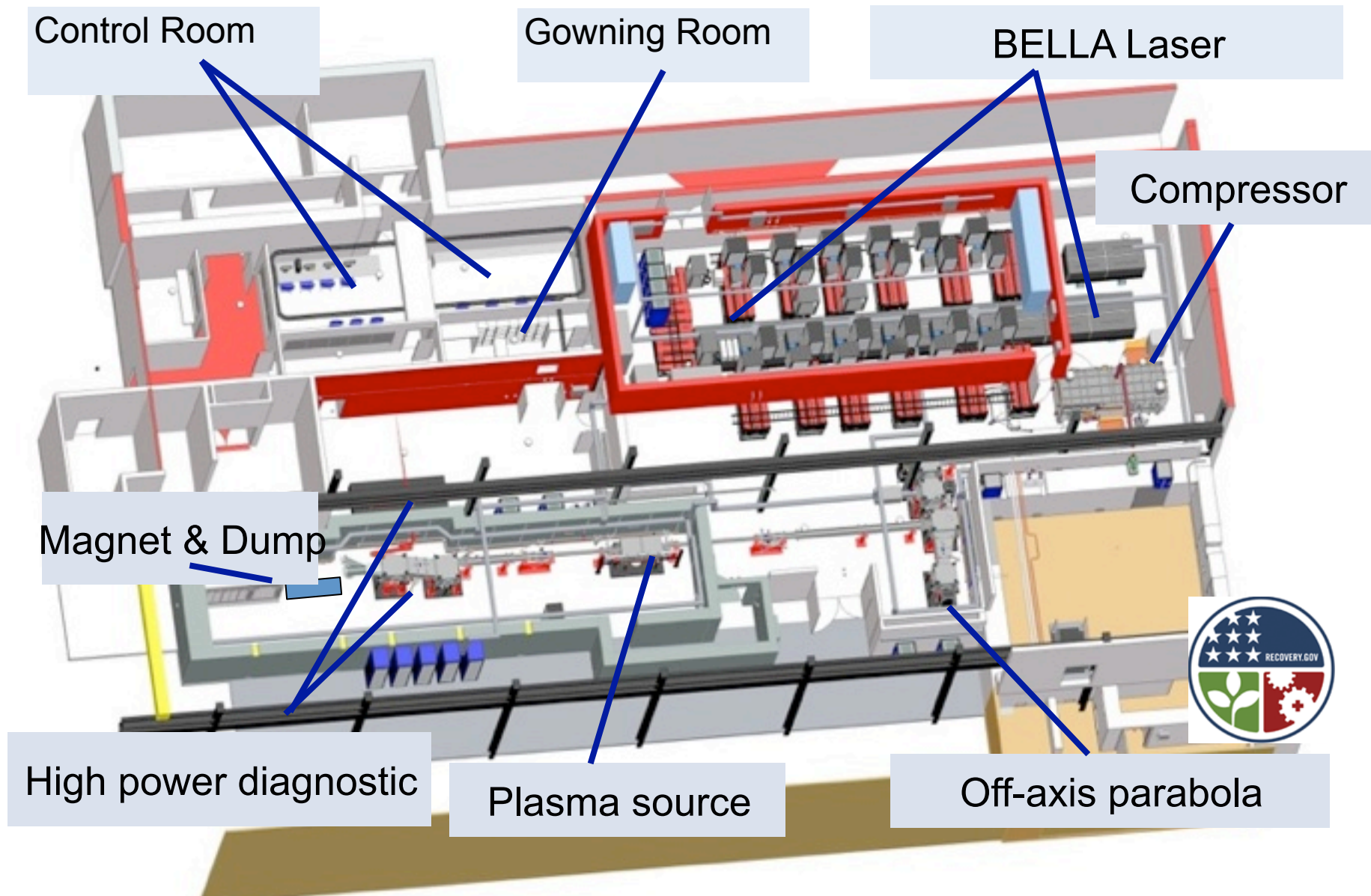
# Petawatt class lasers becoming available with a ten fold expansion planned by 2017-2018 (mainly outside of USA)



- Total peak power of all CPA systems operating today is ~11.5 PW
- By 2018 planned CPA projects will bring total to ~ 127 PW
- Estimates do not include present MJ or planned Exawatt scale projects

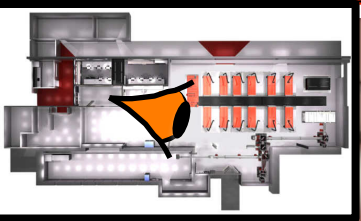
Courtesy: C. Barty, LLNL

# The BELLA facility houses a state-of-the-art PW-laser for laser plasma accelerator science

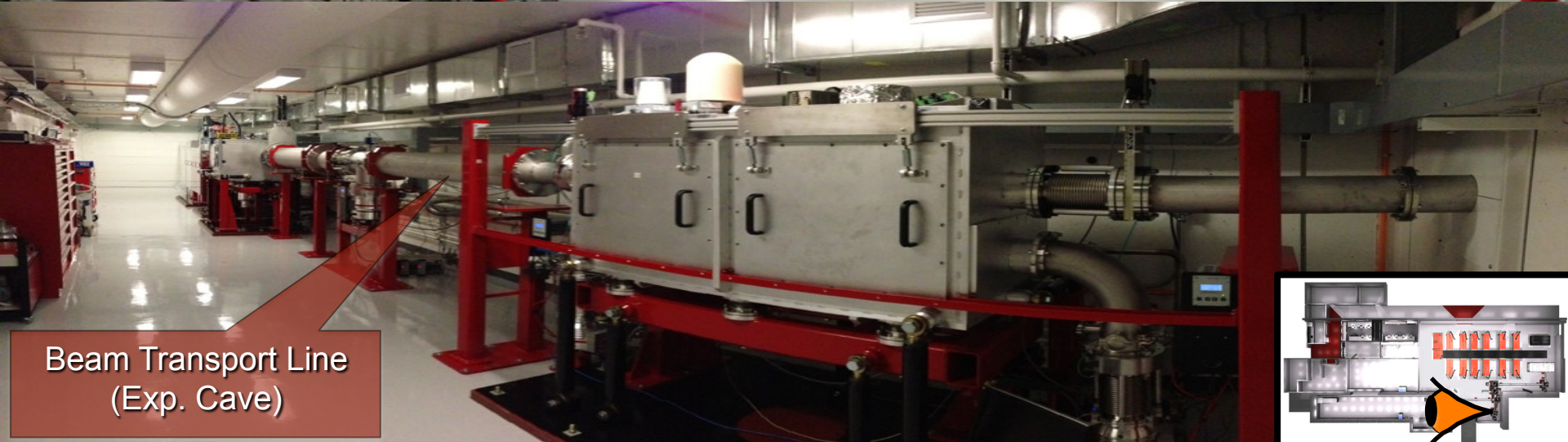




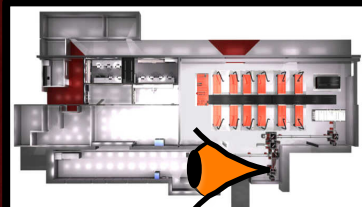
# All major mechanical and electrical systems were installed and commissioned in 2012-2013



Beam Transport Line  
(Laser Bay)

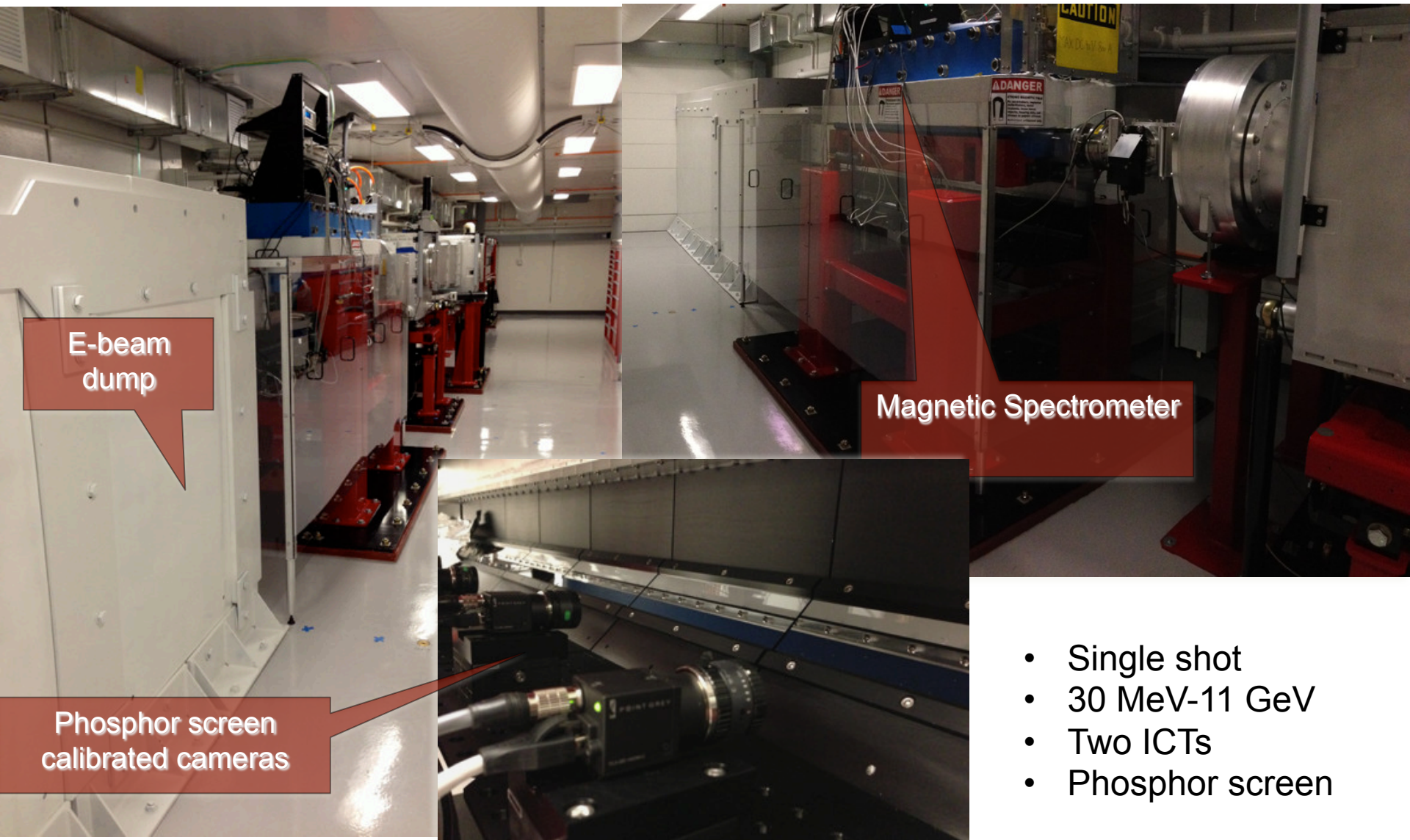


Beam Transport Line  
(Exp. Cave)



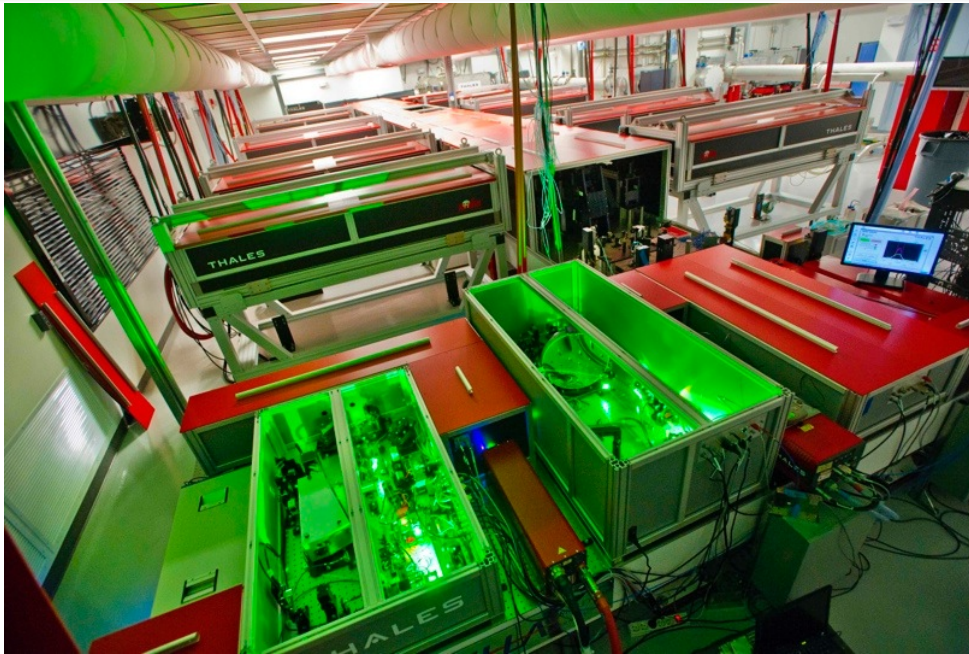


# e-Beam diagnostics include energy, transverse profile and charge transformers

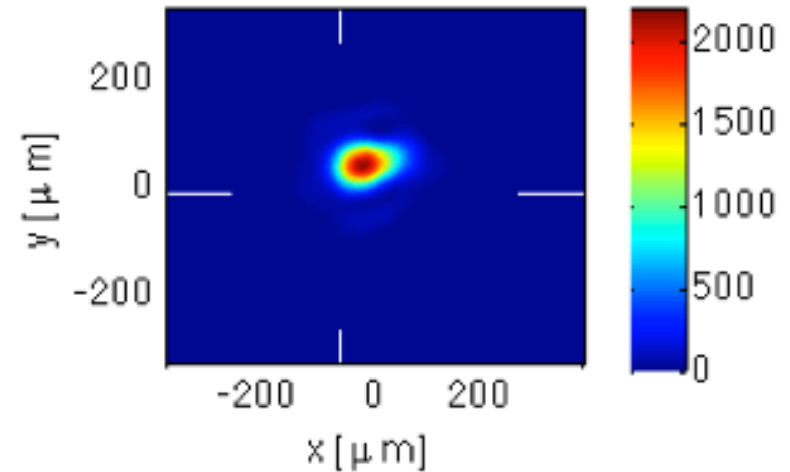


- Single shot
- 30 MeV-11 GeV
- Two ICTs
- Phosphor screen

# BELLA laser operates at $\sim 1$ PW, 1 Hz allowing high intensity laser plasma acceleration experiments



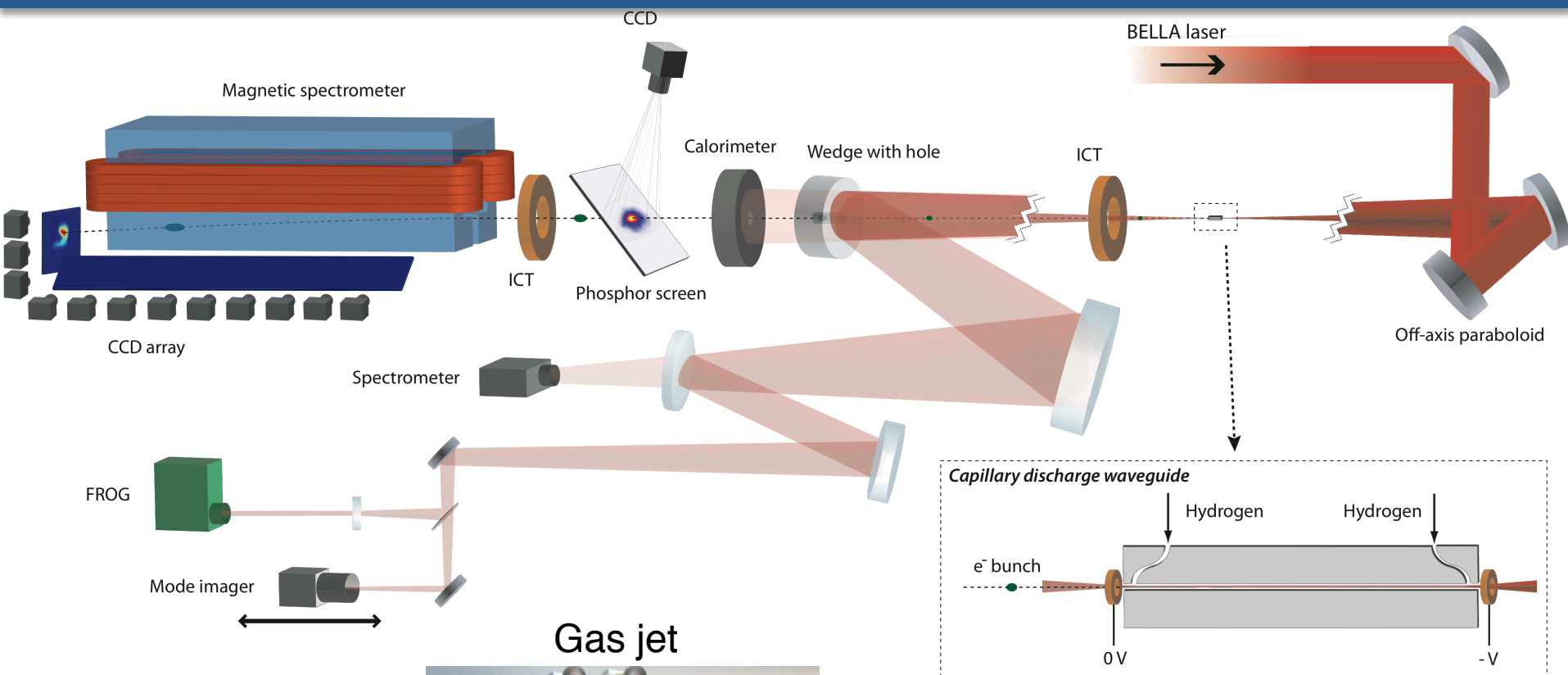
Excellent beam quality



- First commercial Petawatt laser operating at  $> 42$  J in  $< 40$  fs
- Energy stability  $< 0.3$  % rms fluctuation
- Pointing stability  $< 1.2$  micro-rad
- Long focal length mirror:  $\sim 55$  micron spots on target

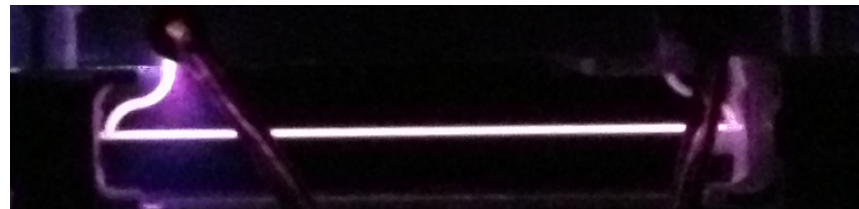
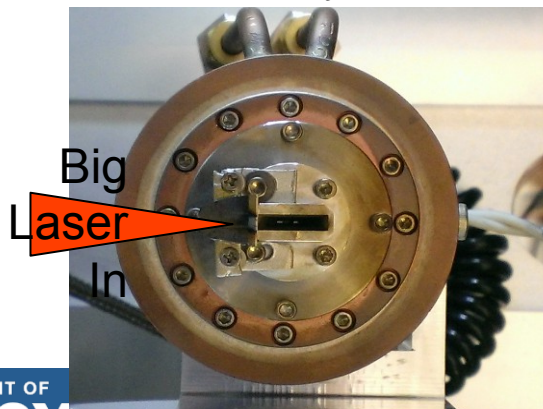


# Experiments at LBNL use the BELLA laser focused by a 14 m focal length off-axis paraboloid onto gas jet or capillary discharge targets



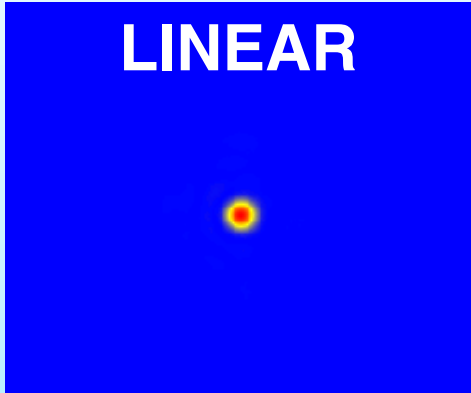
Capillary discharge waveguide

Capillary discharge



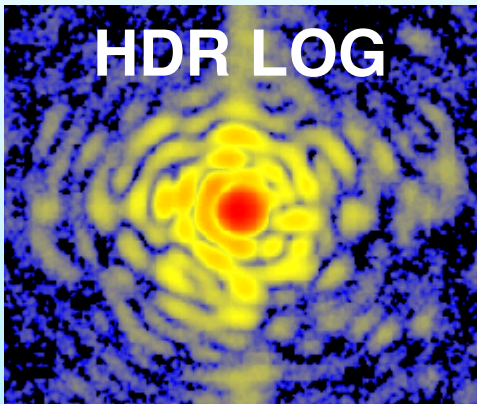
# Optimization of focal quality with deformable mirror is done at all power levels to mitigate thermal lensing in amplifiers

**LINEAR**

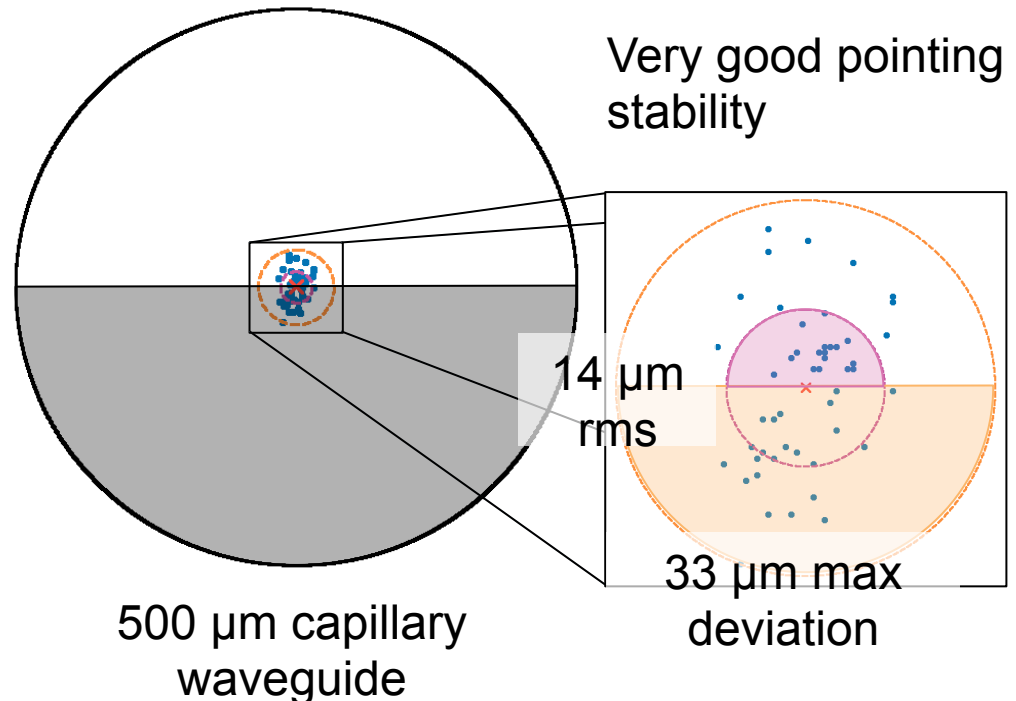
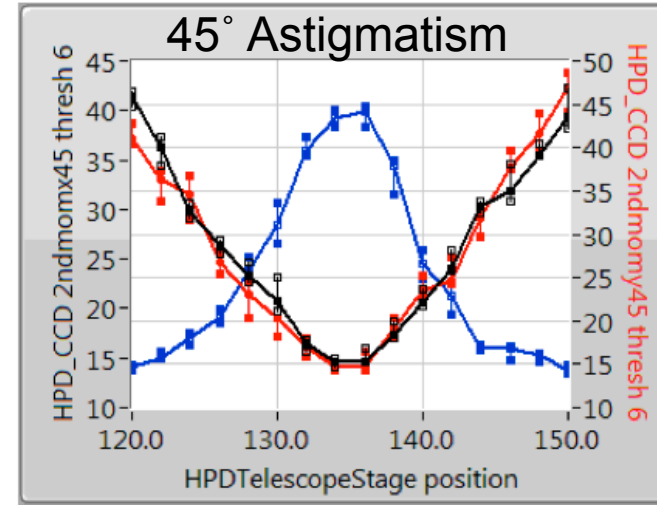
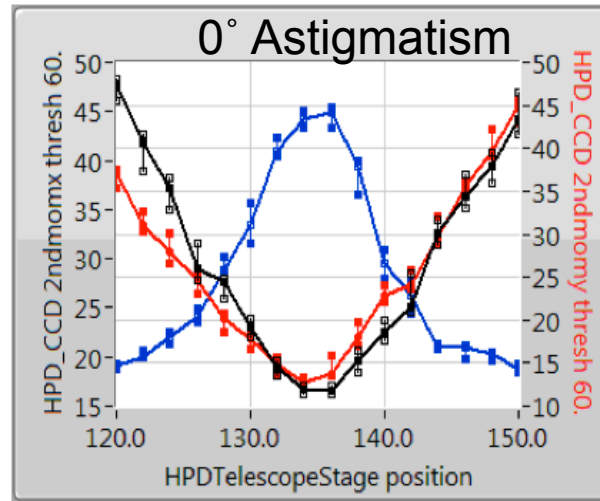


Energy in  $r=w_0$ : 0.82  
Strehl: 0.91

**HDR LOG**



Energy in  $r=w_0$ : 0.78  
Strehl: 0.89





# Pulse shapes are modeled and measured as input for simulations

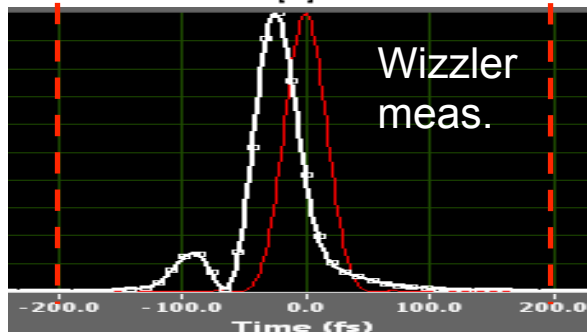
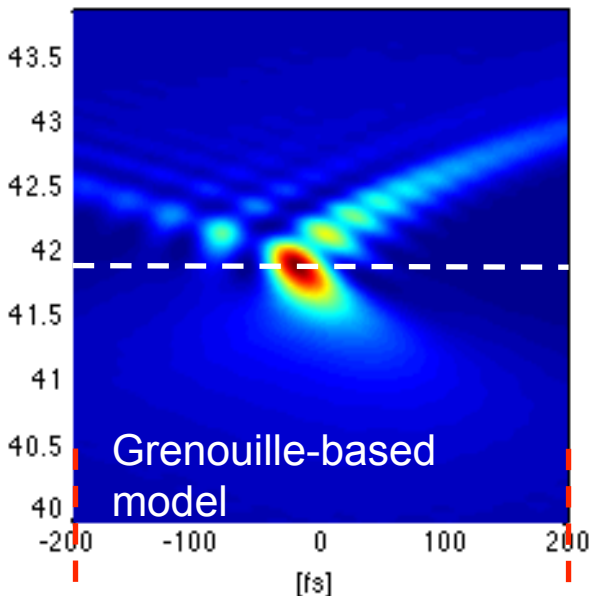
## Reaching 30 fs requires better 3<sup>rd</sup> and 4<sup>th</sup> order compensation

48.195 deg  
Pre-pulse  
19 TW/J

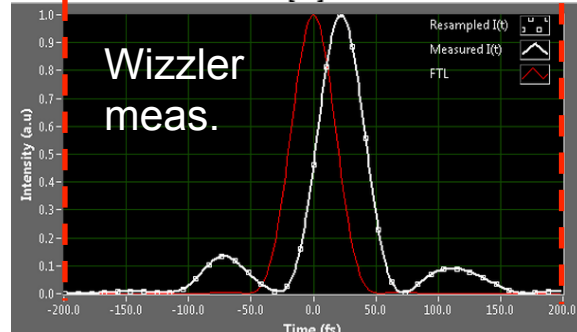
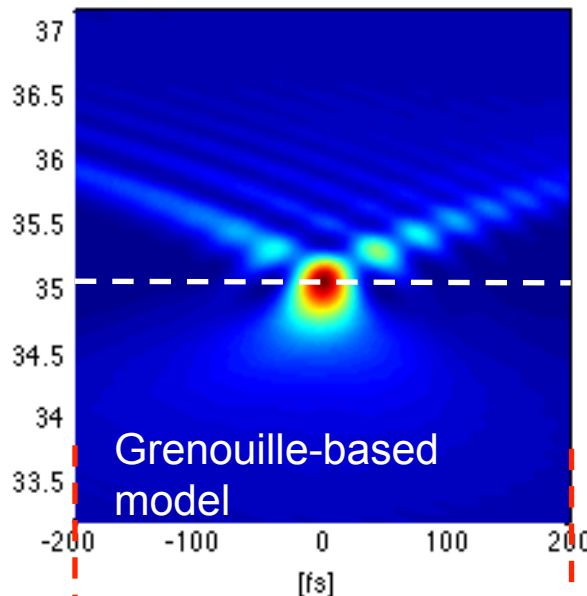
47.99 deg  
Symmetric pulse  
21 TW/J

47.7 deg  
Post-pulse  
17 TW/J

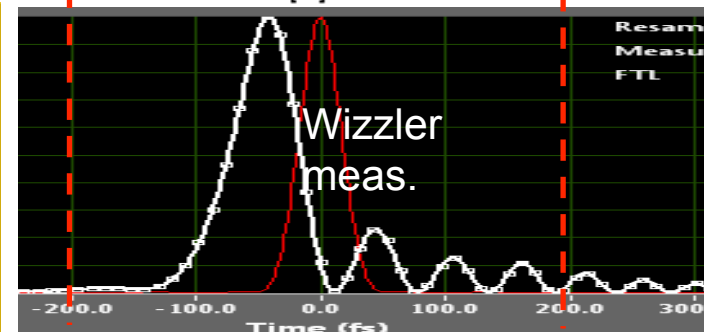
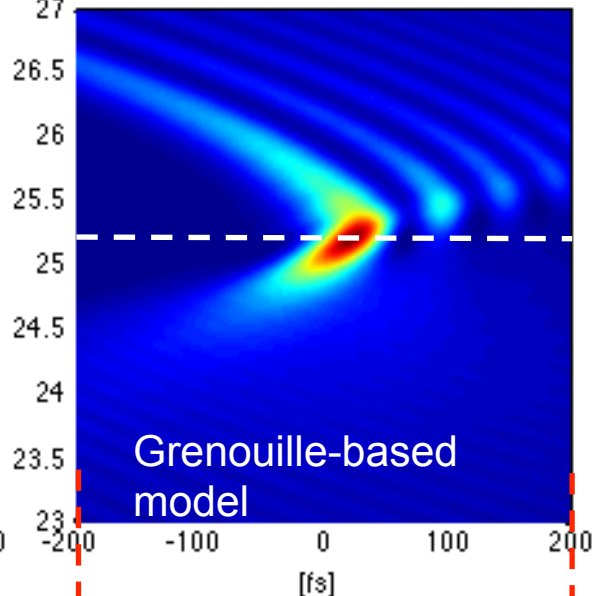
modeled intensity trace at target



modeled intensity trace at target



modeled intensity trace at target



## Capillary discharge runs

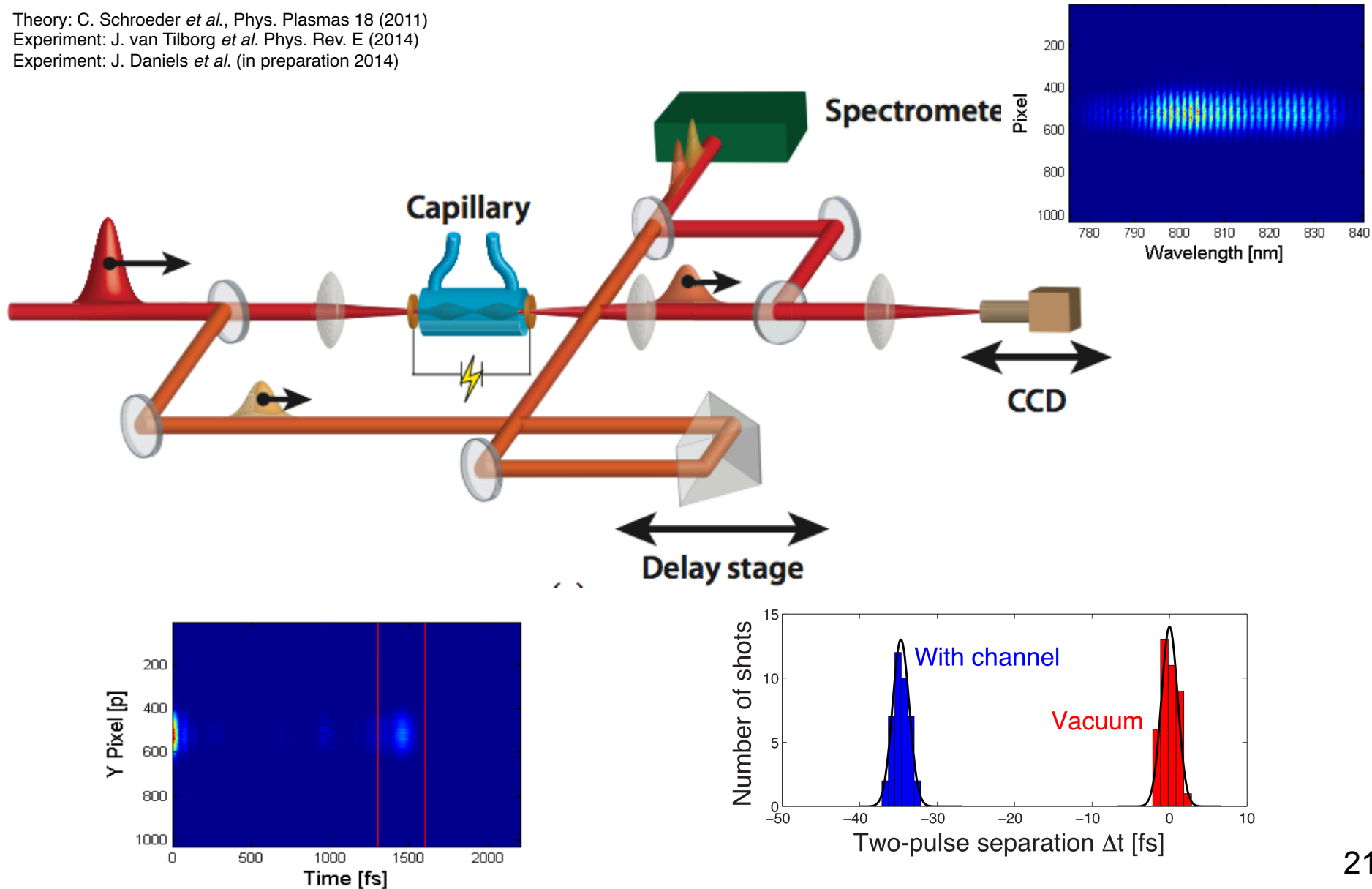


# Longitudinal laser group velocity measurement yields information on density

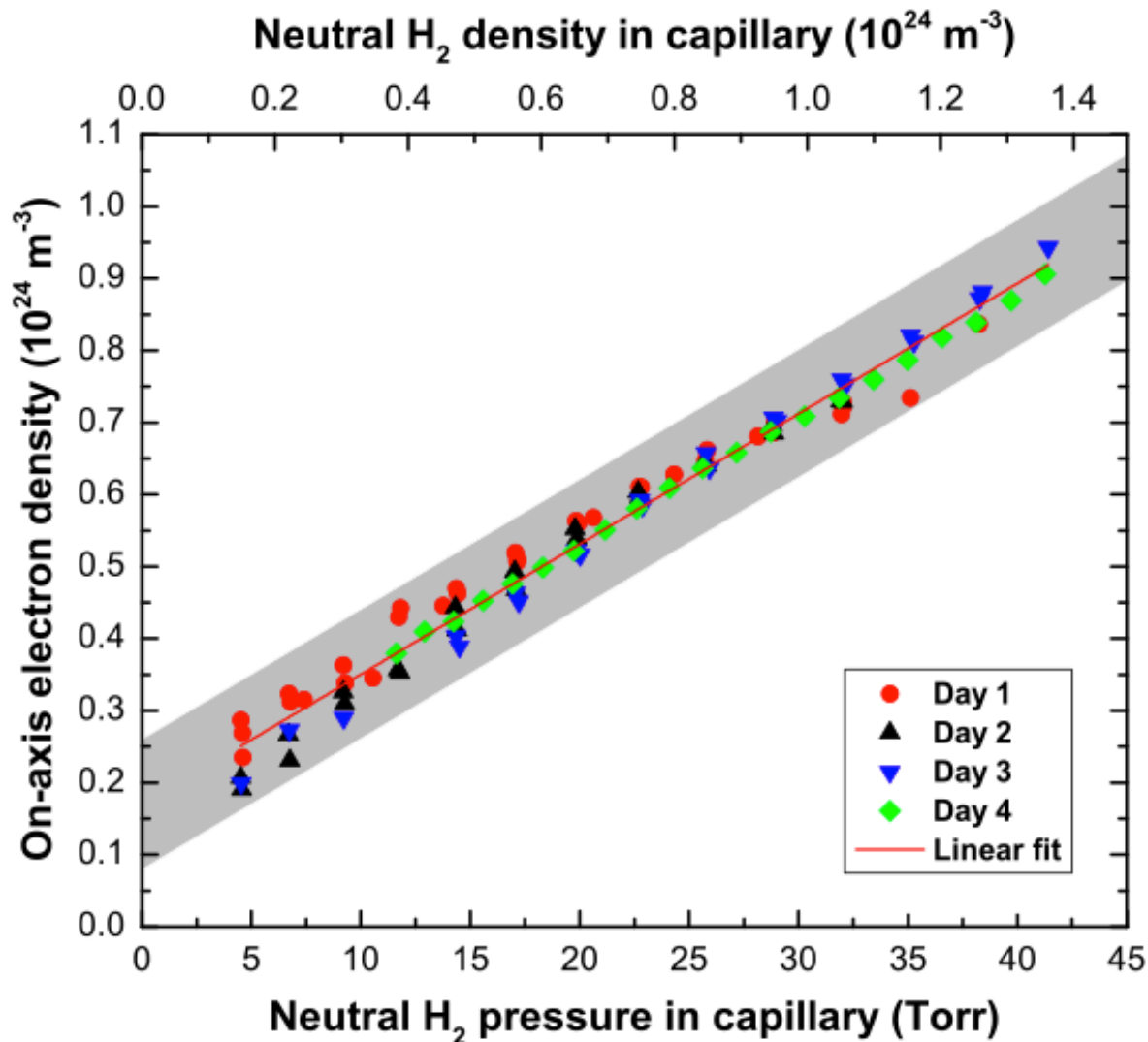
Theory: C. Schroeder *et al.*, Phys. Plasmas 18 (2011)

Experiment: J. van Tilborg *et al.* Phys. Rev. E (2014)

Experiment: J. Daniels *et al.* (in preparation 2014)



# GVD experiment shows that density scales linear with fill pressure and is very repeatable day-to-day

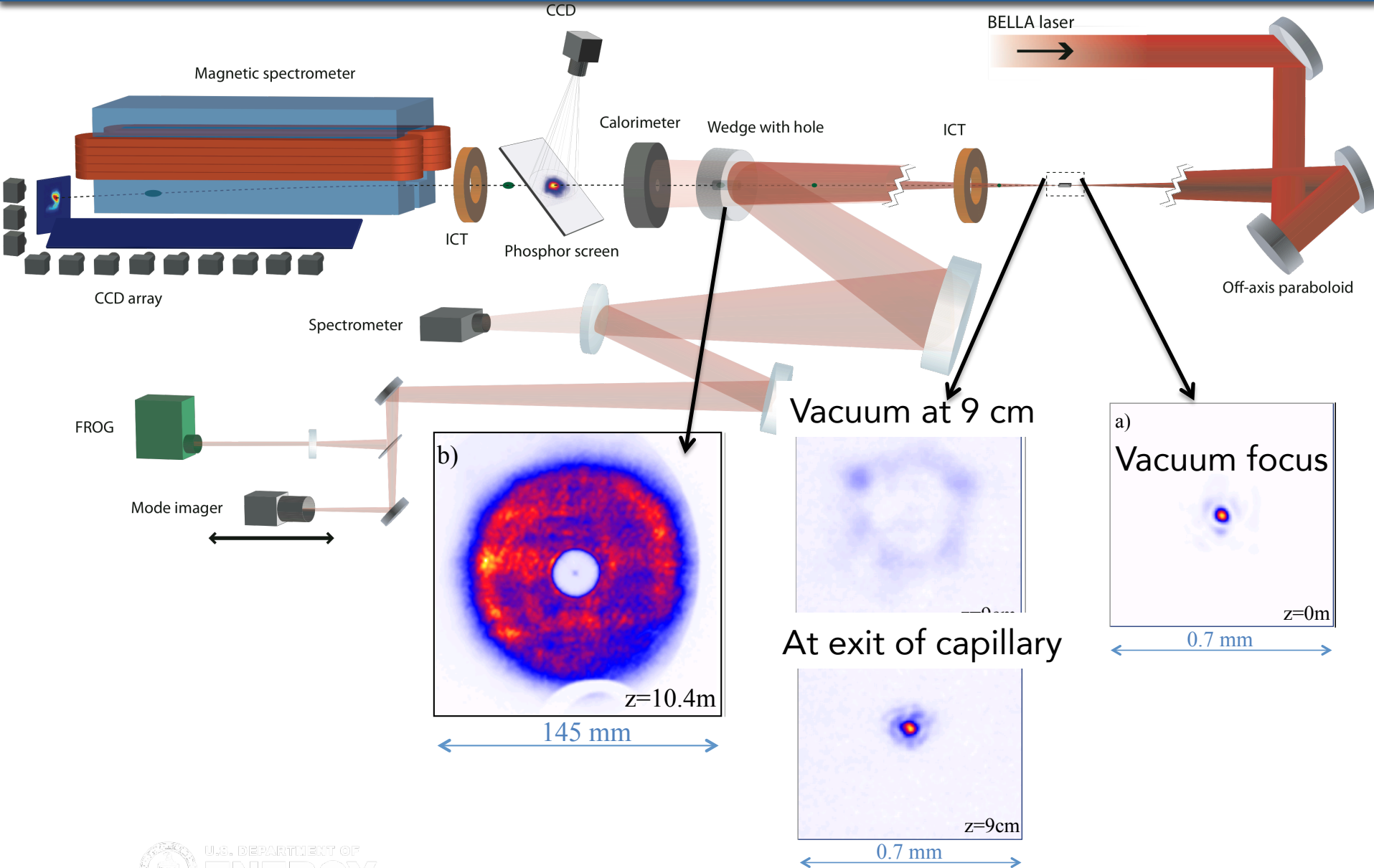


At 40 Torr: (assuming full ionization)  $2.56 \times 10^{18} \text{ cm}^{-3}$  average electron density

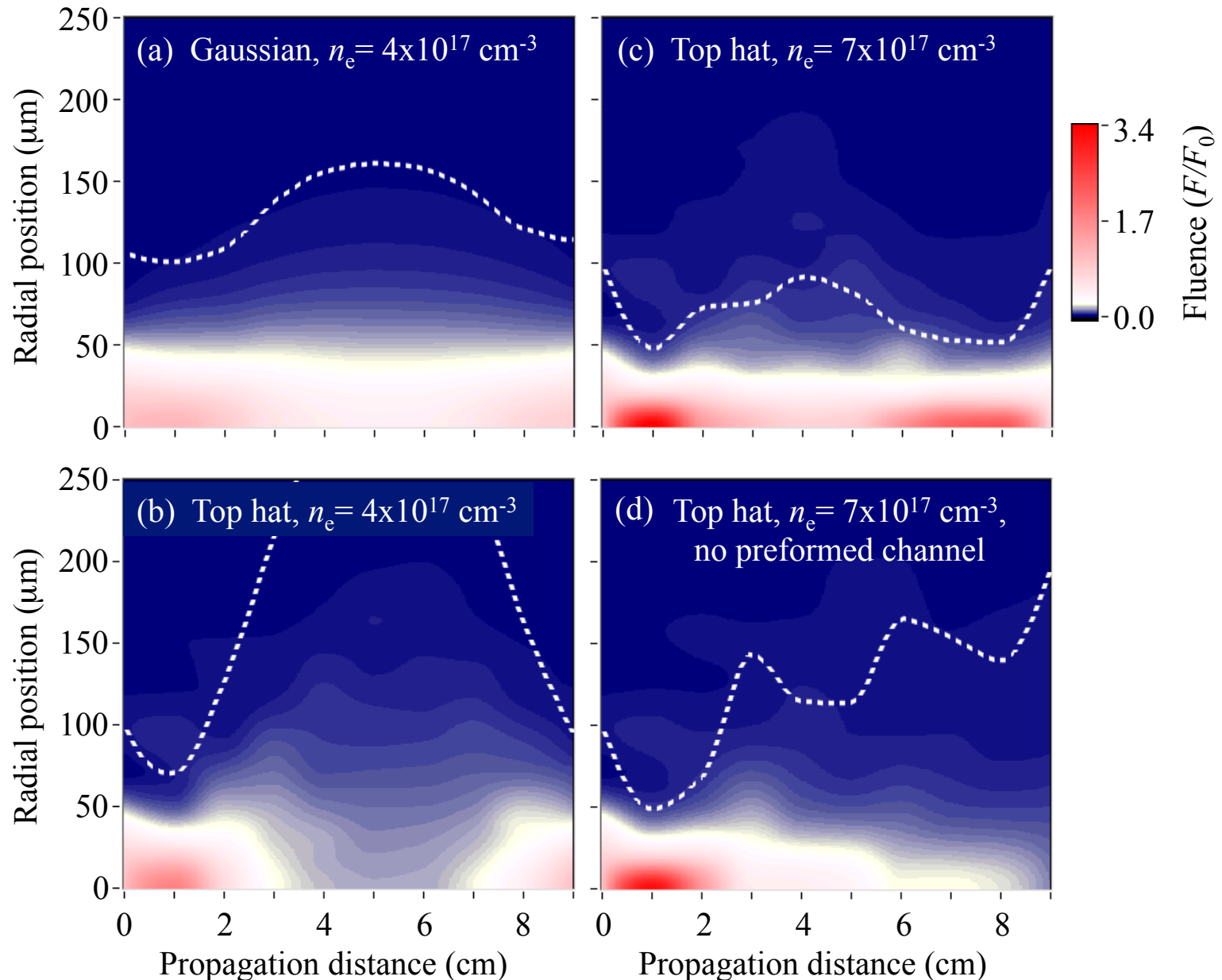


# Vacuum mode looks Gaussian at focus but is near flat-top at 10 meter

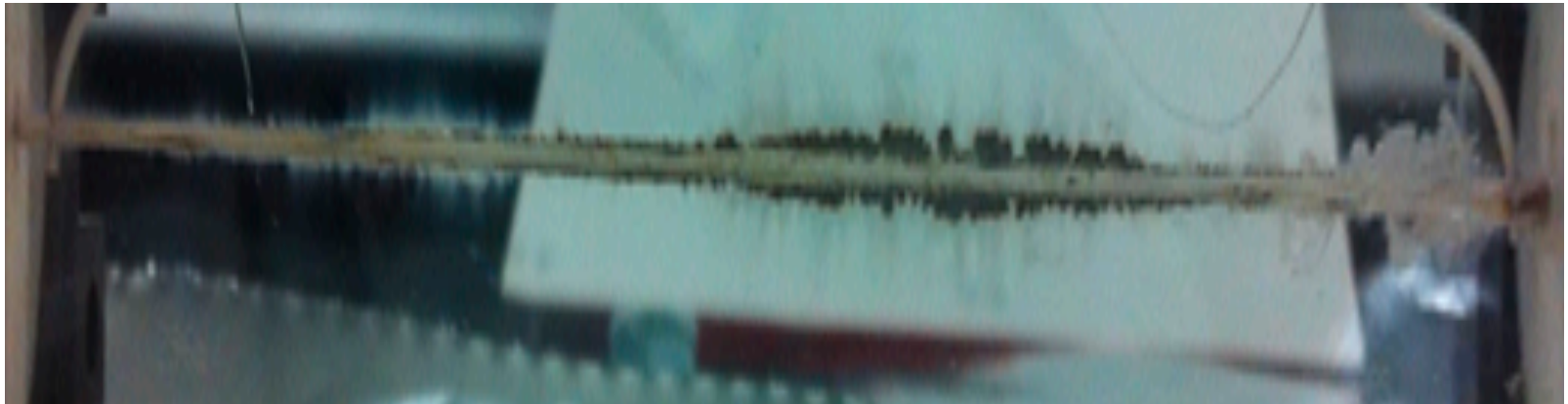
## Low power mode well guided by capillary and looks nearly Gaussian



# Simulation shows top hat beam gives increased fluence at capillary wall compared to Gaussian , higher density compensates



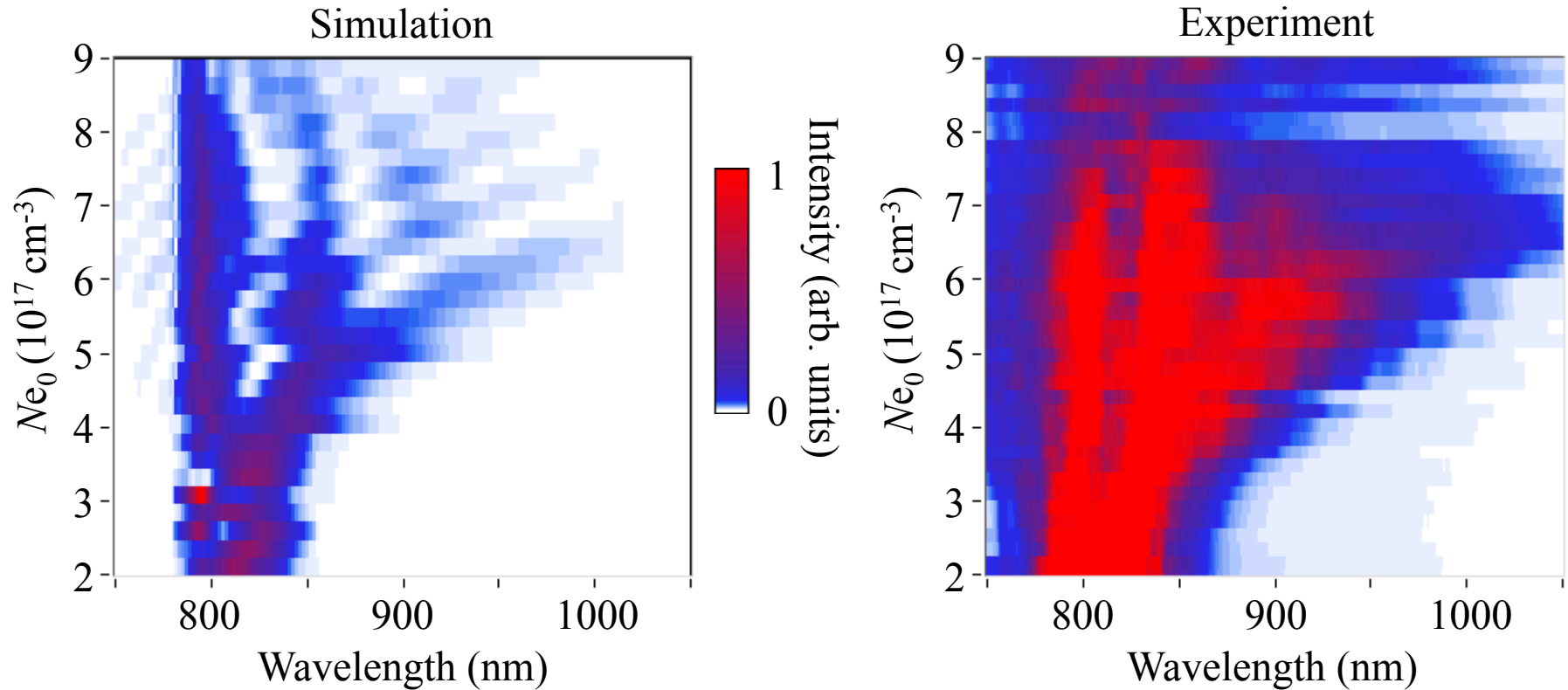
# Under the wrong operating conditions severe damage can be done to the capillary walls



- Measurement of plasma density profile is key for guiding the experiments
  - Centroid based technique for profile shape
    - A.J. Gonsalves et al., PoP 2010
  - Group velocity delay measurement
    - J. van Tilborg et al., PRE 2014
- **In-situ measurement based on spectral redshifting of laser beam**

# Experiment shows similar laser red-shifting as simulation

## Comparison used to cross-calibrate density



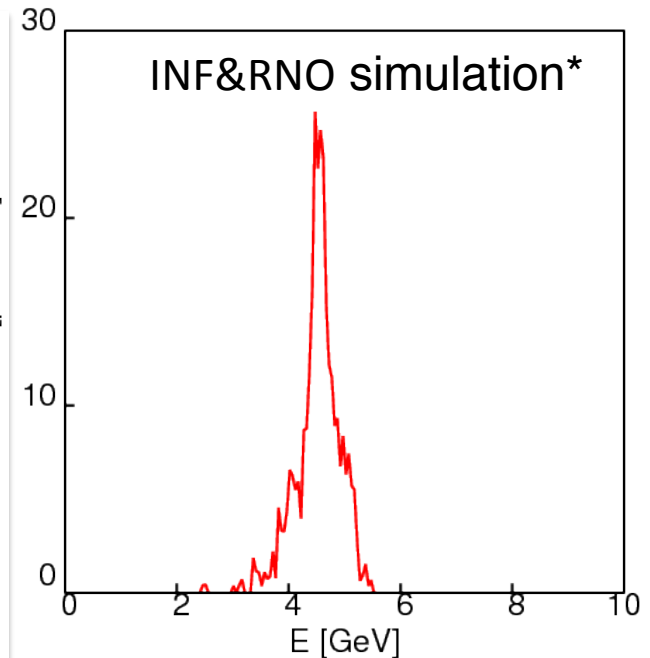
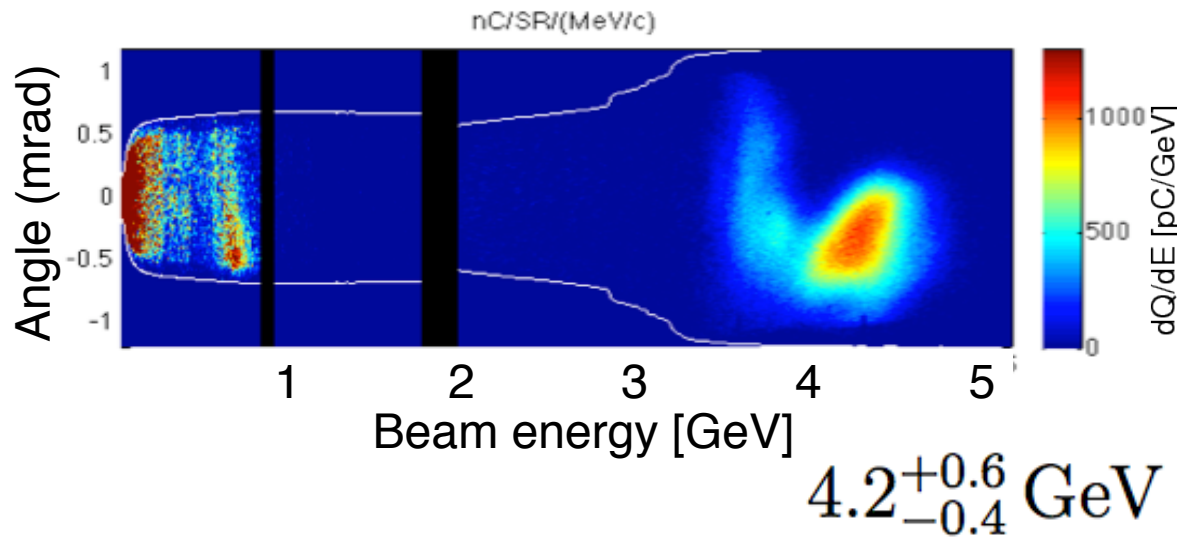
- Previous experiments on redshift in excellent agreement with simulation\*
- Energy  $\sim 7.5\text{J}$ , Pulse length  $\sim 40\text{fs}$ ,  $w_0 \sim 53 \mu\text{m}$ ,  $L_{\text{cap}} = 9\text{cm}$
- Large redshifting indicates deep depletion
- Detector response applied to simulated spectra



# 4.25 GeV beams have been obtained from 9 cm plasma channel powered by 310 TW laser pulses (15 J)

\*C. Benedetti et al., proceedings of AAC2010, proceedings of ICAP2012

Electron beam spectrum



- **Laser** (E=15 J):
  - Measured) longitudinal profile ( $T_0 = 40$  fs)
  - Measured far field mode ( $w_0 = 53 \mu\text{m}$ )
- **Plasma:** parabolic plasma channel (length 9 cm,  $n_0 \sim 6 \times 10^{17} \text{ cm}^{-3}$ )

	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
$\Delta E/E$	6%	3.2%
Charge	$\sim 6$ pC	23 pC
Divergence	0.3 mrad	0.3 mrad

W.P. Leemans et al., submitted



# Parametric studies indicate strong sensitivity to parameters

## Experiments

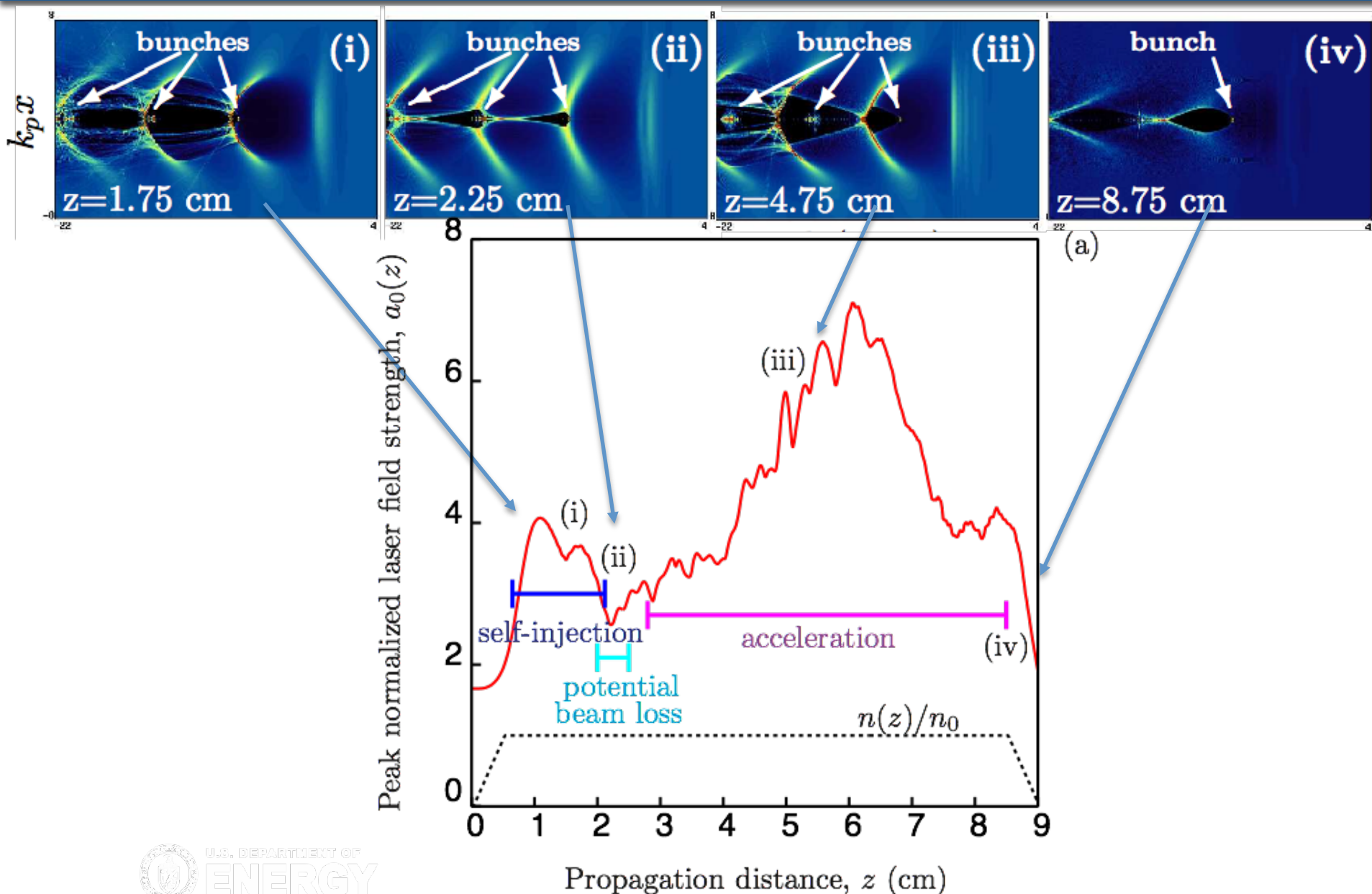
- E-Beams  $>3$  GeV observed in range of  $0.5-1 \times 10^{18} \text{ cm}^{-3}$
- Charge up to 180 pC for the higher densities
- Fluctuation at the 1 GeV level
  - Angular changes ( $\pm 1$  mrad)  $\rightarrow$  0.5 GeV inaccuracy
  - Density fluctuations from group velocity dispersion:  $\pm 0.15 \times 10^{17} \text{ cm}^{-3}$
  - Laser fluctuations  $a_0 \sim \pm 0.08$

## Simulations

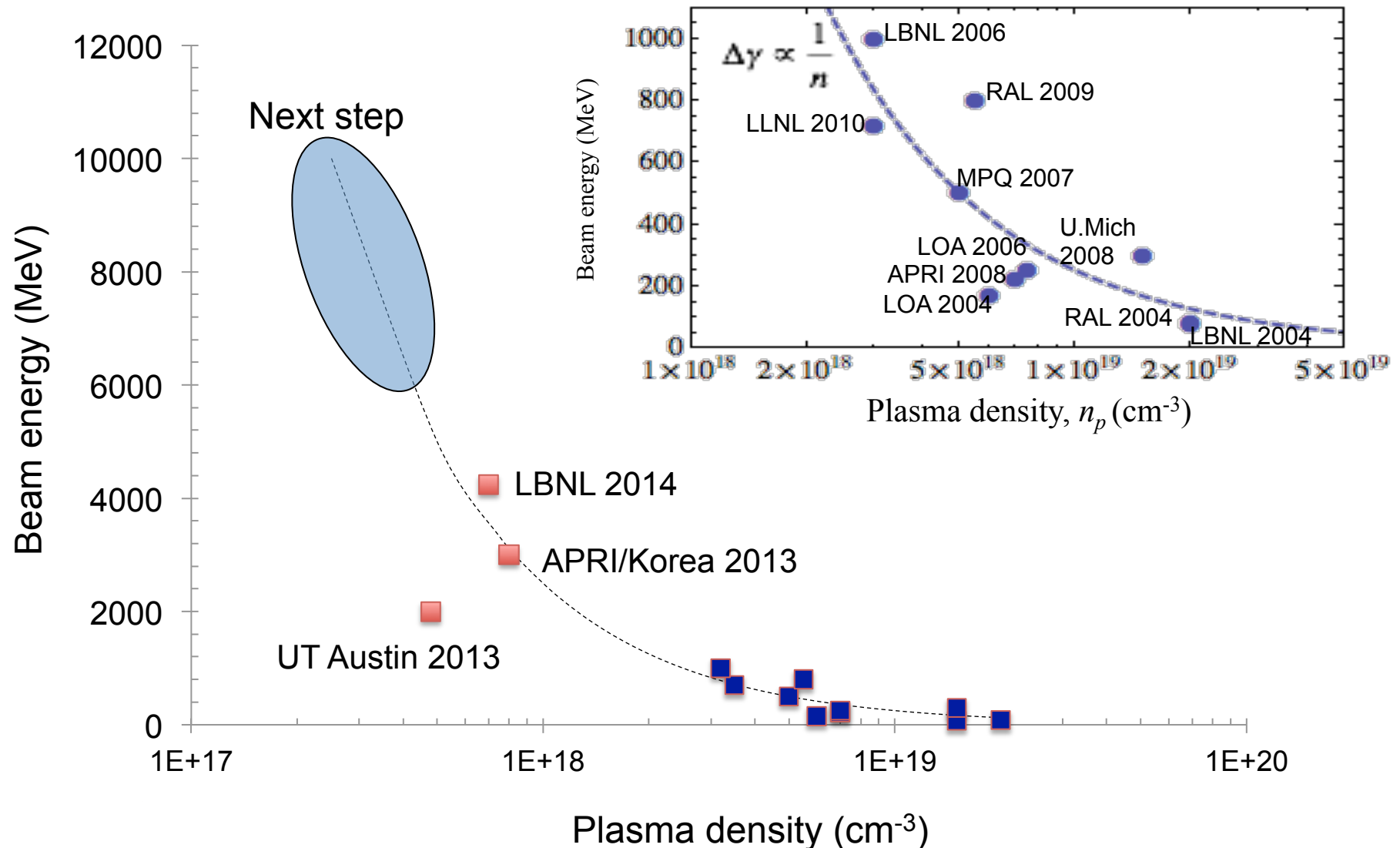
Density ( $10^{17} \text{ cm}^{-3}$ )	$E_L$ (J)	$a_0$	Near-field profile	Energy (GeV)	Charge (pC)
6.5	16	1.66	Top-hat	3.9	15
7.0	16	1.66	Top-hat	4.3	50
7.0	15	1.61	Top-hat	3.7	35

# Electron trapping and acceleration is complex in this regime

## Simulations based on measured input parameters

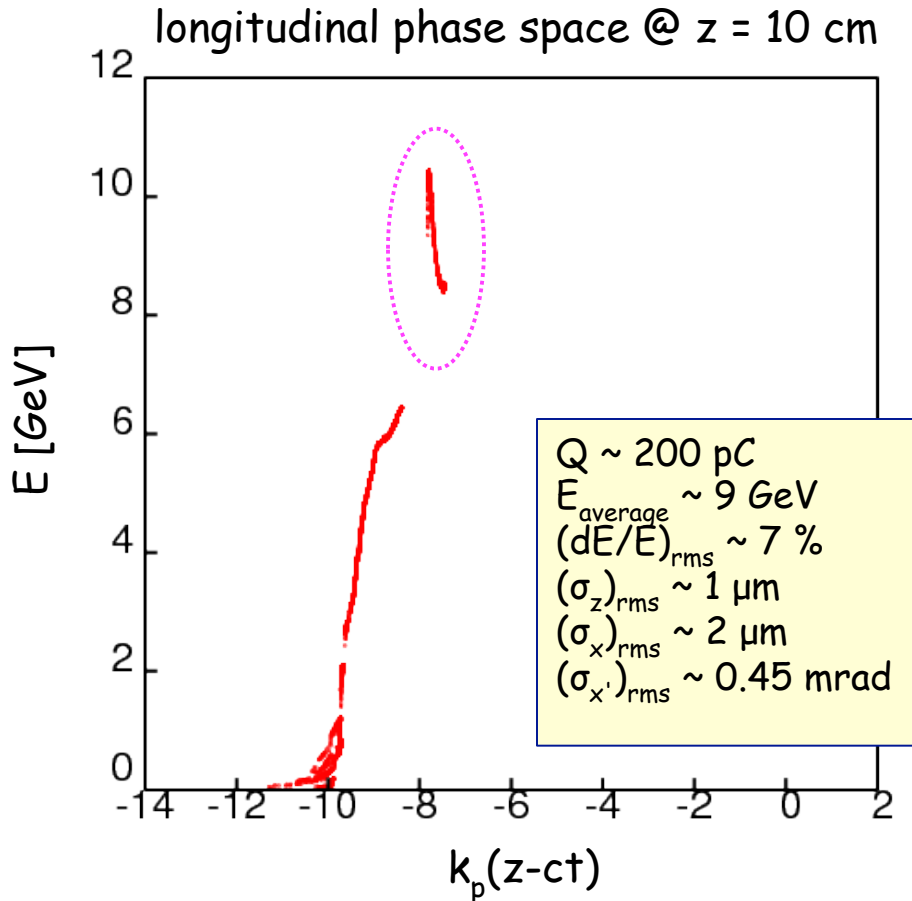


# New experiments also confirm energy gain scales with $1/n$ 10 GeV requires further lowering of density



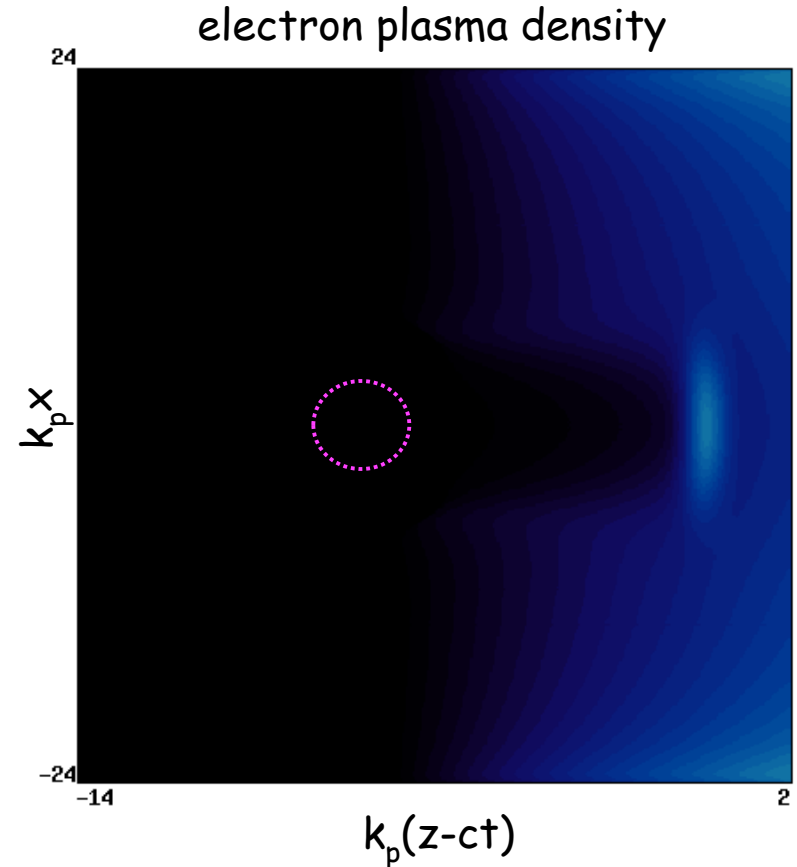


# 10 GeV-class quasi-monoenergetic beams can be obtained in $\sim 10$ cm capillary in non-linear regime



Initial  $a_0 \sim 3.5-4.0$

Plasma density  $\sim 3 \times 10^{17}$   $\text{cm}^{-3}$



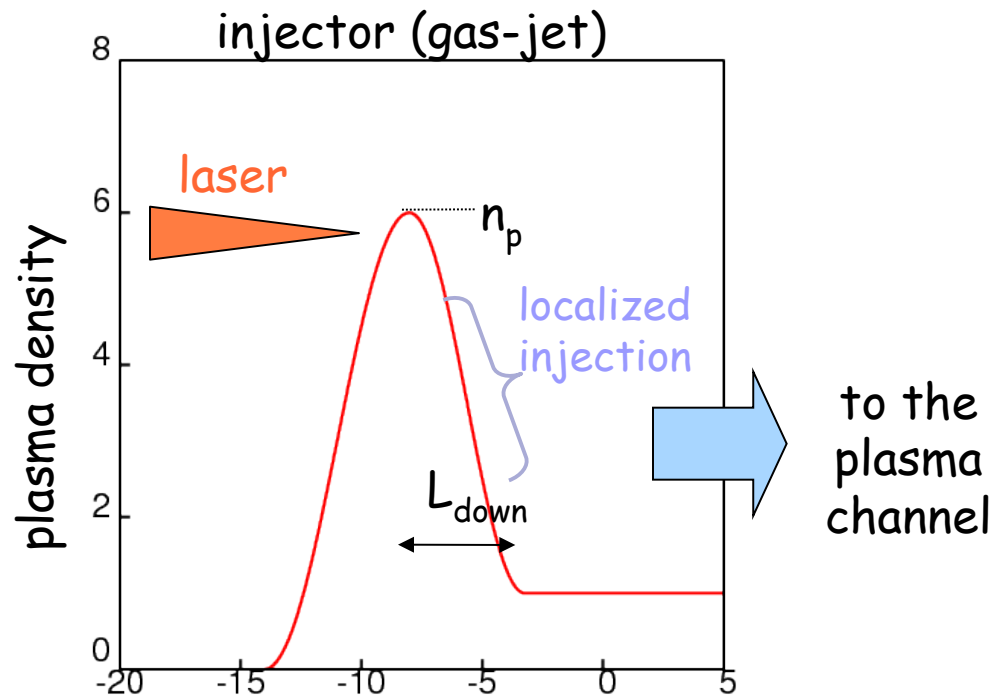
Laser heater required to deepen channel

N.A. Bobrova et al., Physics of Plasmas **20**, 020703 (2013)

# INF&RNO simulation of a 10 GeV-class stage in the quasi-linear regime: injector + accelerator

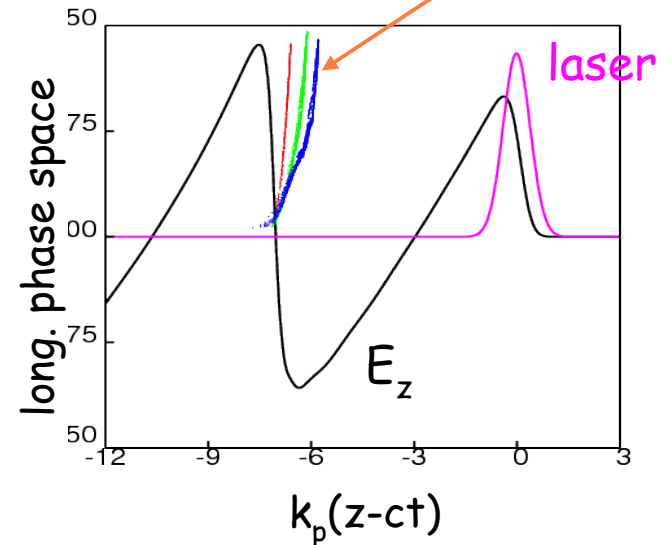
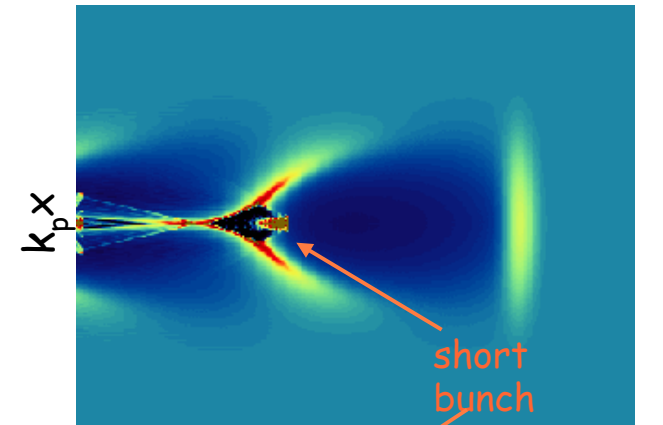
$T_{\text{laser}} \approx 100 \text{ fs}$ ,  $a_0 = 1.7$ , plasma channel  $n_0 \approx 2 \times 10^{17} \text{ e/cm}^3 \Rightarrow$  requires triggered injection\*

injector (negative density gradient)



→ injection phase can be accurately controlled through  $n_p$  and  $L_{\text{down}}$

electron density (after gas-jet)



\* Gonsalves *et al.*, Nature Phys. (2011)

# Tunable electron beams can be produced with jet + capillary module using laser focus control

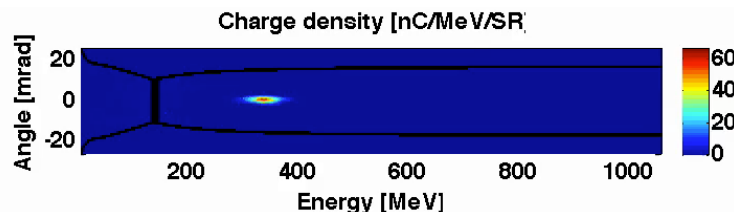
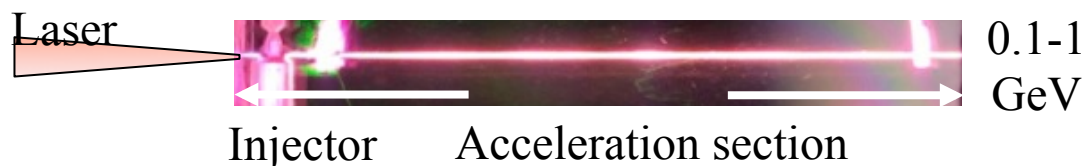
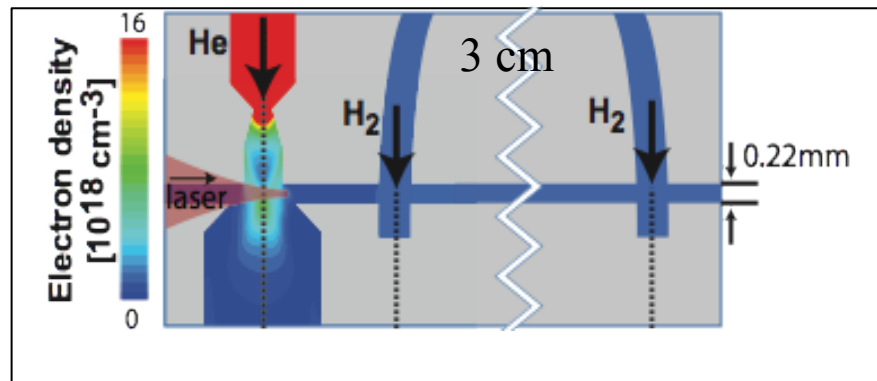
LETTERS

PUBLISHED ONLINE: 21 AUGUST 2011 | DOI: 10.1038/NPHYS2071

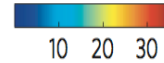
nature  
physics

## Tunable laser plasma accelerator based on longitudinal density tailoring

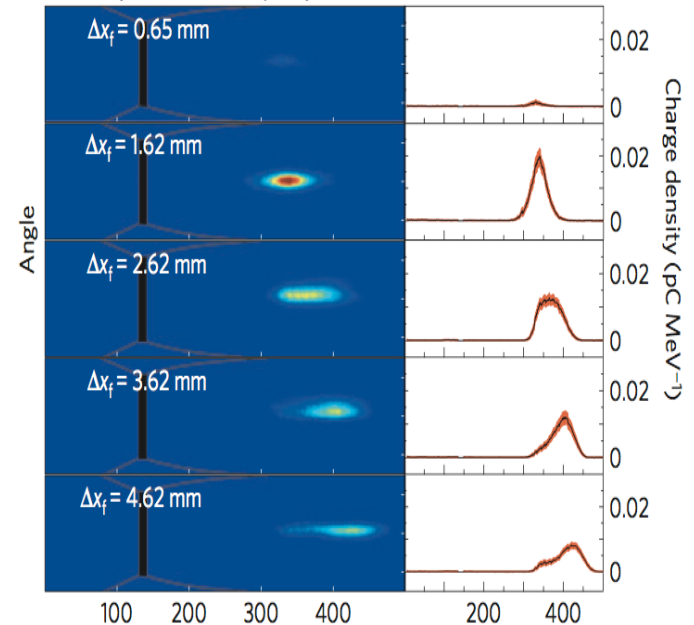
A. J. Gonsalves<sup>1</sup>, K. Nakamura<sup>1</sup>, C. Lin<sup>1,2</sup>, D. Panasenkov<sup>1†</sup>, S. Shiraishi<sup>1,3</sup>, T. Sokollik<sup>1,4</sup>, C. Benedetti<sup>1</sup>, C. B. Schroeder<sup>1</sup>, C. G. R. Geddes<sup>1</sup>, J. van Tilborg<sup>1</sup>, J. Osterhoff<sup>1†</sup>, E. Esarey<sup>1</sup>, C. Toth<sup>1</sup> and W. P. Leemans<sup>1,4\*</sup>



Charge density  
(nC MeV<sup>-1</sup> sr<sup>-1</sup>)



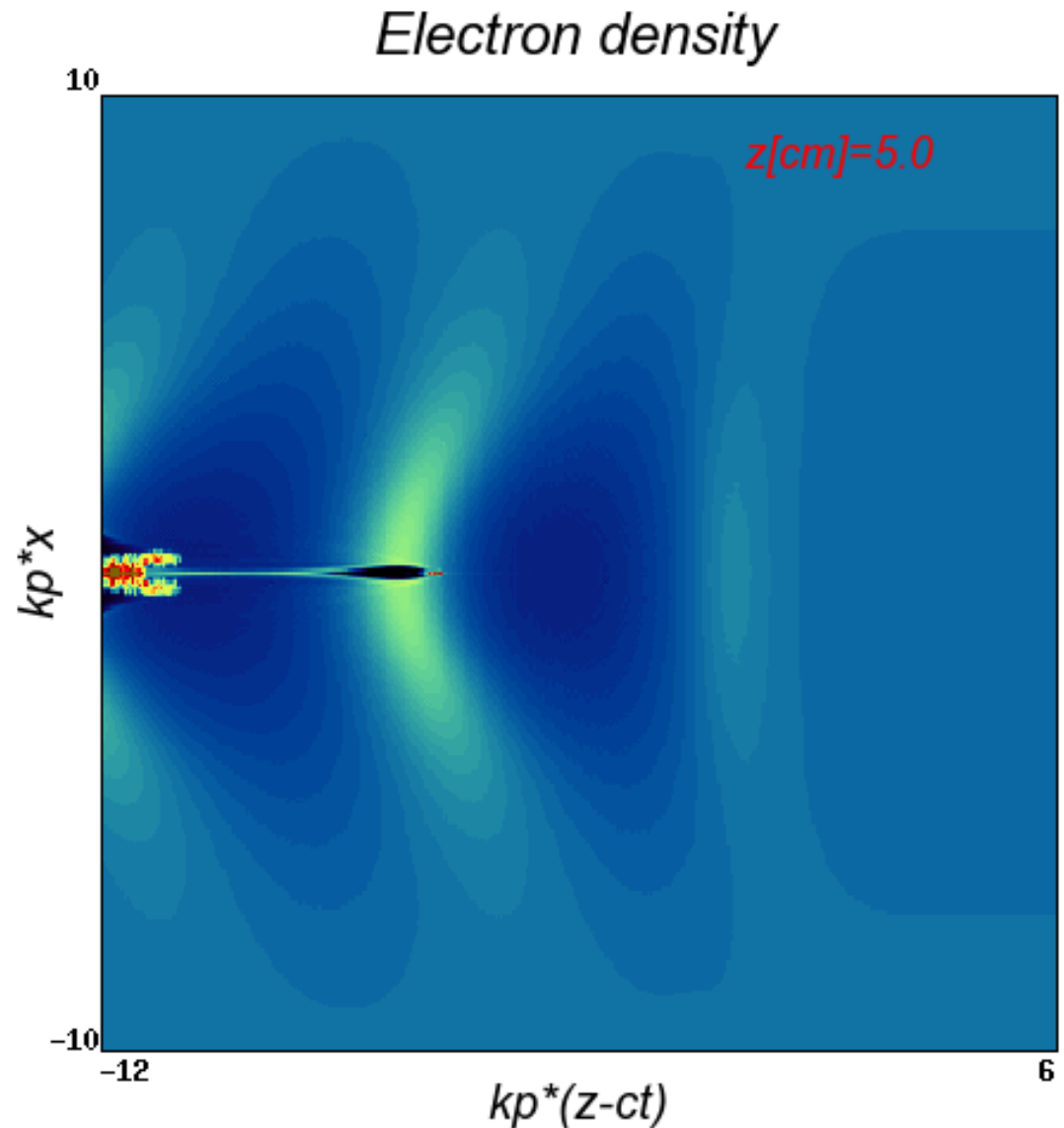
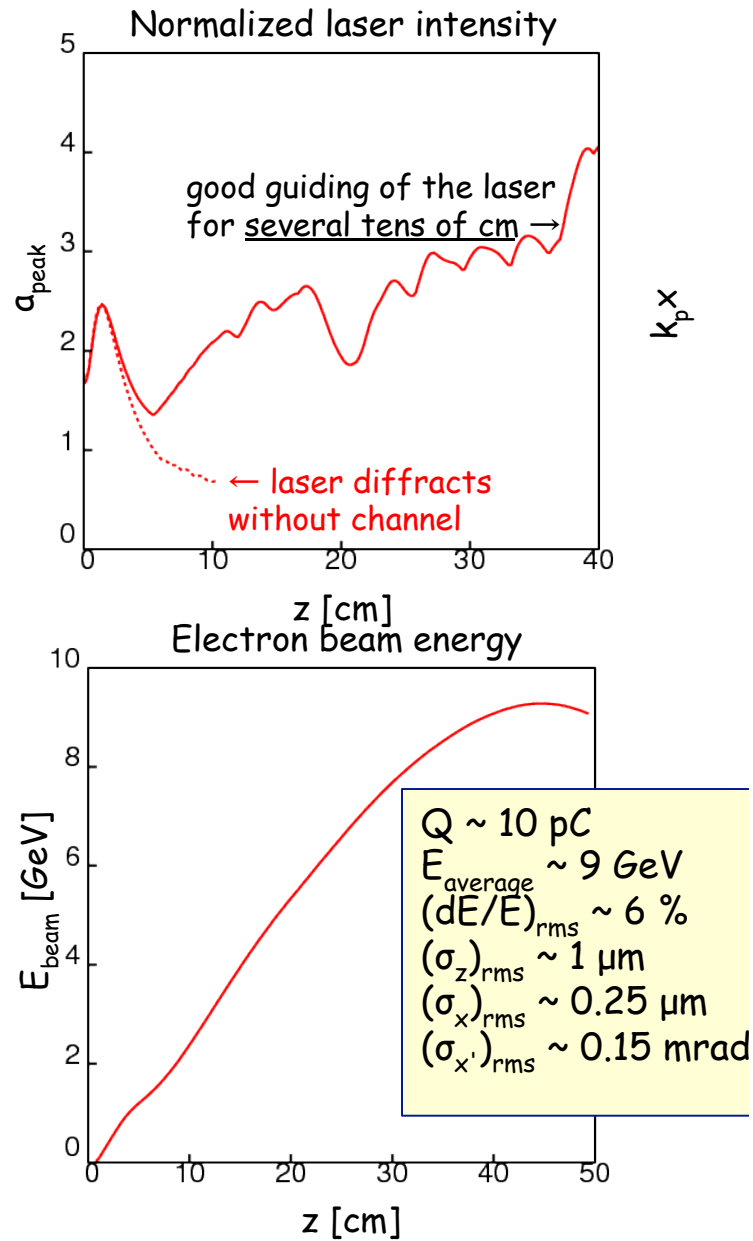
↑ Jet only ↓ Jet and capillary



Energy variation < 2 % rms  
Charge variation < 6 % rms  
Divergence change < 0.57 mrad rms

A.J. Gonsalves et al., Nature Physics 2011

# Low energy spread beams produced in 40 cm acceleration length





# Outline

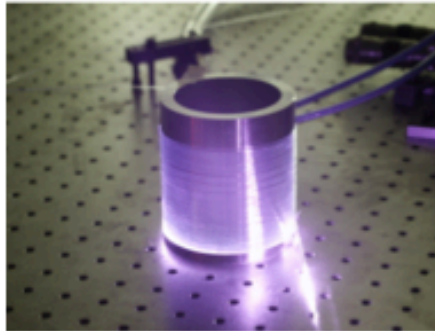
- Staging of two independently powered LPAs
- Experiments with BELLA
- **Towards high average power operations**

# Many applications need higher average power

1-10 kW  
Security Apps  
(5-10 yrs)

Laser plasma  
accelerator (today)

10-100 W



## Workshop on Laser Technology for Accelerators

*Summary Report*

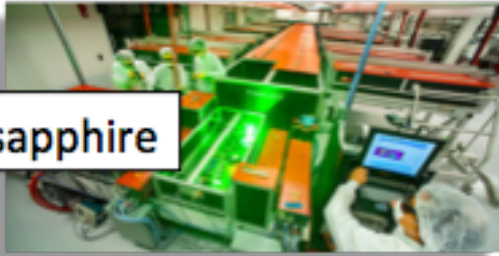
January 23-25, 2013

Collider  
(>20 yrs)  
>100 kW

# For k-BELLA, revolutionary new laser technology will be required and a path is emerging

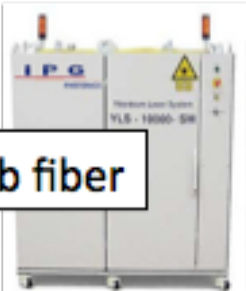
## State-of-the-art:

Ti:sapphire



40J, 40fs, 1Hz

Yb fiber



50kW, 30% eff., CW



Yb fiber



100kHz, 45fs, 1mJ

## Upgrade path:

Higher rep rate,  
efficiency

Short pulses

Higher energy,  
efficiency

## Goal:

3J  
100fs  
3kW  
20% eff.  
1kHz



# Achieving high average power with ultrafast lasers will most likely rely on some form of beam combining or pulse stacking

- Just increase power to existing laser technology?
  - It would break, wrong technology
- 10kW, 30% efficient fiber lasers exist, but CW
  - Ultrafast lasers peak power limited to  $\sim 1$  mJ
- Solution: coherent combining
  - Space: 10,000 lasers?
  - Time: 100 pulses from one laser



- Novel methods combine (“stacks”) pulses in time
- A high energy system would do both

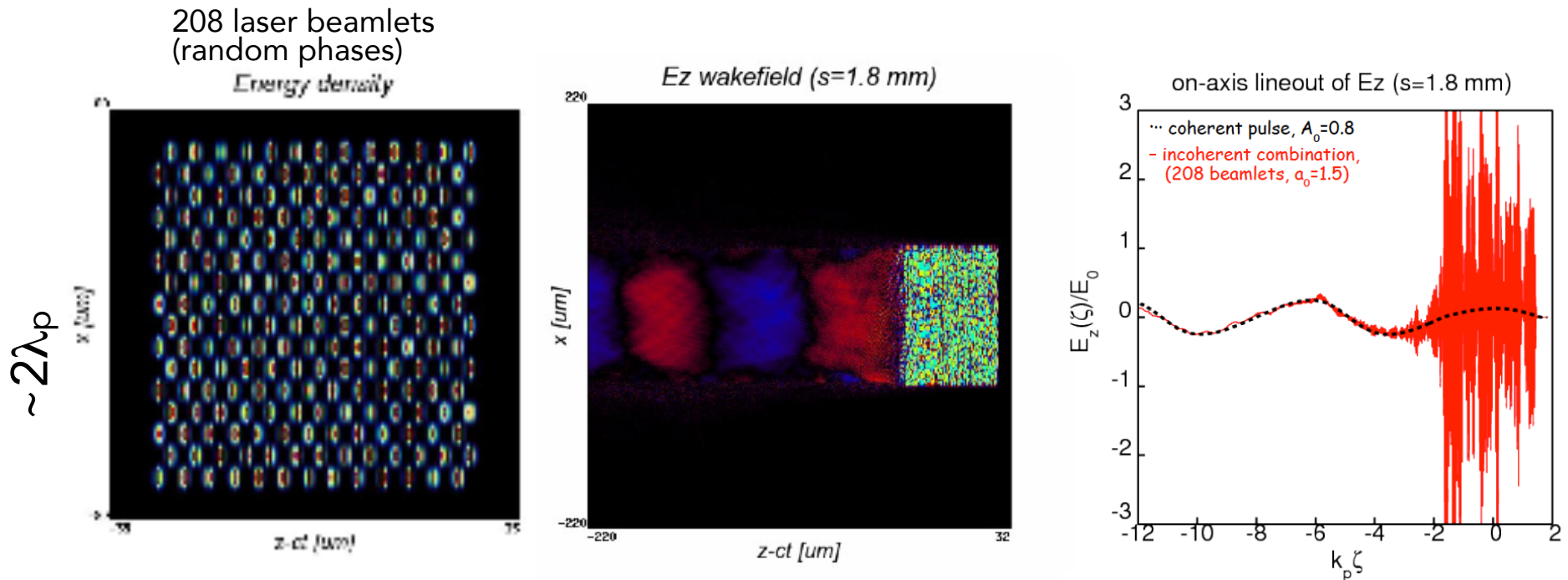




# A new concept has emerged that could radically change requirements on lasers

## ► Plasma wave excitation by incoherent laser pulses: path to high-average and high-peak power lasers for LPA

- Benedetti et al., Phys. Plasmas (2014)



- Same integrated momentum gain for coherent pulse and incoherent combination
- Will have significant impact in thinking about future high average power lasers

# Summary

- Petawatt class lasers are enabling multi-GeV laser plasma accelerators
- Experiments with gas jet, gas cell and capillary discharges
  - Capillary discharge LPA reached 4.2 GeV ebeams using  $\sim 15$  J in  $\sim 40$  fs pulses
  - Laser guiding is key to achieving the highest energy with the lowest laser power
    - Laser mode has important impact on performance
    - Operation at lower density and mode matching can be challenging
- Next phase experiments:
  - Decouple injection and acceleration
  - Towards 10 GeV: longer structures at lower density, including channel depth control with laser heater
- Concepts for high average power lasers are being developed
  - Incoherent combining may relax requirements
- Plans for a high average power laser demonstrator (3 J at 1 kHz) being developed
  - k-BELLA: 1 GeV at 1 kHz

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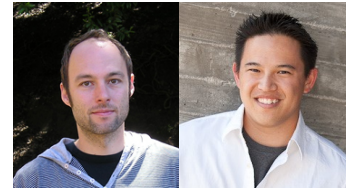


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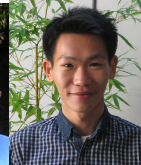
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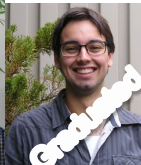
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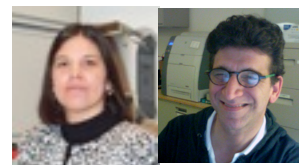


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